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A concluding study of the altitude determination deficiencies of the Service Aircraft Instrumentation Package (SAIP)

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Monterey, California

THESIS

A CONCLUDING STUDY OF THE ALTITUDE DETERMINATION DEFICIENCIES OF THE SERVICE AIRCRAFT INSTRUMENTATION PACKAGE (SAIP)

by

Daniel G. Sergent

Thesis Advisor: Oscar Biblarz

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Previous research at the Naval Postgraduate School addressed the aerodynamic effects that caused the altitude determination errors in the Service Aircraft Instrumentation package (SAIP). This thesis builds on the previous work and focused on establishing a correction for the SAIP using both aerodynamic and atmospheric corrections to the Extended Area Test System (EATS) system evaluator program.

By using a quadratic function of Mach number to estimate the Cp, the aerodynamic errors can be reduced to enable the SAIP to measure altitude correctly to within 100 ft for velocities up to Mach 0.8. This correction is used to modify the static pressure read by the SAIP. Further flight tests will have to be accomplished to determine the correction for a range of altitudes and aircrafts. The atmospheric errors can be corrected by analyzing the sounding data generated by the Geophysics Department at Pt. Mugu and substituting actual lapse rate information into the standard altitude equation. This model is shown to predict altitudes to within 200 feet up through 60,000 feet.

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A Concluding Study in the Altitude Determination Deficiencies of the Service Aircraft Instrumentation Package (SAIP).

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

Previous research at the Naval Postgraduate School addressed the aerodynamic effects that caused the altitude determination errors in the Service Aircraft Instrumentation package (SAIP). This thesis builds on the previous work and focused on establishing a correction for the SAIP using both aerodynamic and atmospheric corrections to the Extended Area Test System (EATS) system evaluator program.

By using a quadratic function of Mach number to estimate the Cp, the aerodynamic errors can be reduced to enable the SAIP to measure altitude correctly to within 100 ft for velocities up to Mach 0.8. This correction is used to modify the static pressure read by the SAIP. Further flight tests will have to be accomplished to determine the correction for a range of altitudes and aircrafts. The atmospheric errors can be corrected by analyzing the sounding data generated by the Geophysics Department at Pt. Mugu and substituting actual lapse rate information into the standard altitude equation. This model is shown to predict altitudes to within 200 feet up through 60,000 feet.

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LIST OF SYMBOLS

AOA	Angle of Attack
β	Temperature Lapse Rate
Cp	Pressure Coefficient: $\Delta p/q$
dP	Differential change in pressure
dz	Differential change in altitude
$\Delta p/q$	Static Pressure Error
ΔZ	Difference in the altitude reported by the A-6 and by the SAIP
EATS	Extended Area Test System
g	Gravitational Constant
g_{ave}	Gravitational Constant at 22,800 meters, ($\approx$ 9.725)
GIS	Ground Interrogation Station
g_o	Sea-level Gravitational Constant
GPS	Geopositional Satellite System
γ	Specific Heat Ratio of Air ($\approx$ 1.4)
h	Geopotential Altitude
hp	Pressure Altitude
MOCS	Master Operations Control Station
M_∞	Free Stream Mach Number
MHz	Megahertz
NAWCWPNS	Naval Air Warfare Center, Weapons Division
P	Pressure
P_o	Sea-Level Pressure

Ps	Static Pressure
P_{SAIP}	Pressure read by the SAIP
P_{sf}	Pressure read at the GIS and MOCS sites
P_{∞}	Free Stream Pressure
q	Dynamic Pressure
R	Specific Gas Constant
R^3	Relay, Responder, Recorder
SAIP	Service Aircraft Instrumentation Package
T_{iso}	Temperature at the start of the isothermal region
T_o	Sea-Level Temperature
T_{sf}	Temperature read at the GIS and MOCS sites
VAC	Volts, Alternating Current
VDC	Volts, Direct Current
V_{∞}	Free Stream Velocity

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I. INTRODUCTION

A. BACKGROUND

This is the fourth and final effort at the Naval Postgraduate school on the altitude determination errors of the Service Aircraft Instrumentation Package (SAIP). The findings from the first report indicated that there were some problems with the way the system was electrically grounded [Ref. 1], and established the foundation for future study by reducing the available raw data and developing the experimental techniques. The second report [Ref. 2] resolved the grounding error, and focused on the aerodynamic nature of the problem. The third report quantified the aerodynamic errors and showed the aircraft pressure field to be a dominant source of error [Ref. 3]. In this thesis, methods used for the first three studies are revisited, and means by which an accurate correction code can be established are developed.

1. System Description

The SAIP mounts on any aircraft with the LAU-7A (series) launcher station. It provides the Extended Area Test System (EATS) at the Naval Air Warfare Center, Point Mugu, California (NAWCWPNS) with three dimensional tracking information. The EATS utilizes 22 Ground Reference Stations each with a Relay, Responder, Recorder (R^3) unit that relay signals to and from the SAIPs. By measuring the time it takes the signal to travel from an R^3 unit to the SAIP and back, the EATS computer determines the distance from several Ground Reference Stations to the SAIP, and computes the location of the aircraft through multilateration. The EATS computer takes this location in 3-D space along with the altitude computed using the static pressure read at the pitot-static probe on the SAIP to predict a best-guess altitude.

The SAIP, shown in Figure 1, consist of a five inch diameter tube which houses the electronic systems, and a fiberglass nose cone that holds air-data and antenna subsystems. The SAIP is completely self-contained requiring only 115 VAC and 28 VDC power from the aircraft. It sends static pressure, air speed, attitude, and weapon system status to the EATS computer at a carrier frequency of 141 MHz.

The SAIP is intended to operate in all flight regimes including takeoff and landing, supersonic and subsonic speeds.

2. System Performance

The functional specifications for altitude determination for the SAIP require "the altitude error in 50 percent of the track updates shall be less than the larger of 100 feet or three percent of the participant altitude" [Ref. 4]. Flight tests were performed on 23 May 1989 with A-6 and A-7 aircraft, and again on 7 September 1989 using another A-6. Errors reported were on the order of 500-600 feet at an

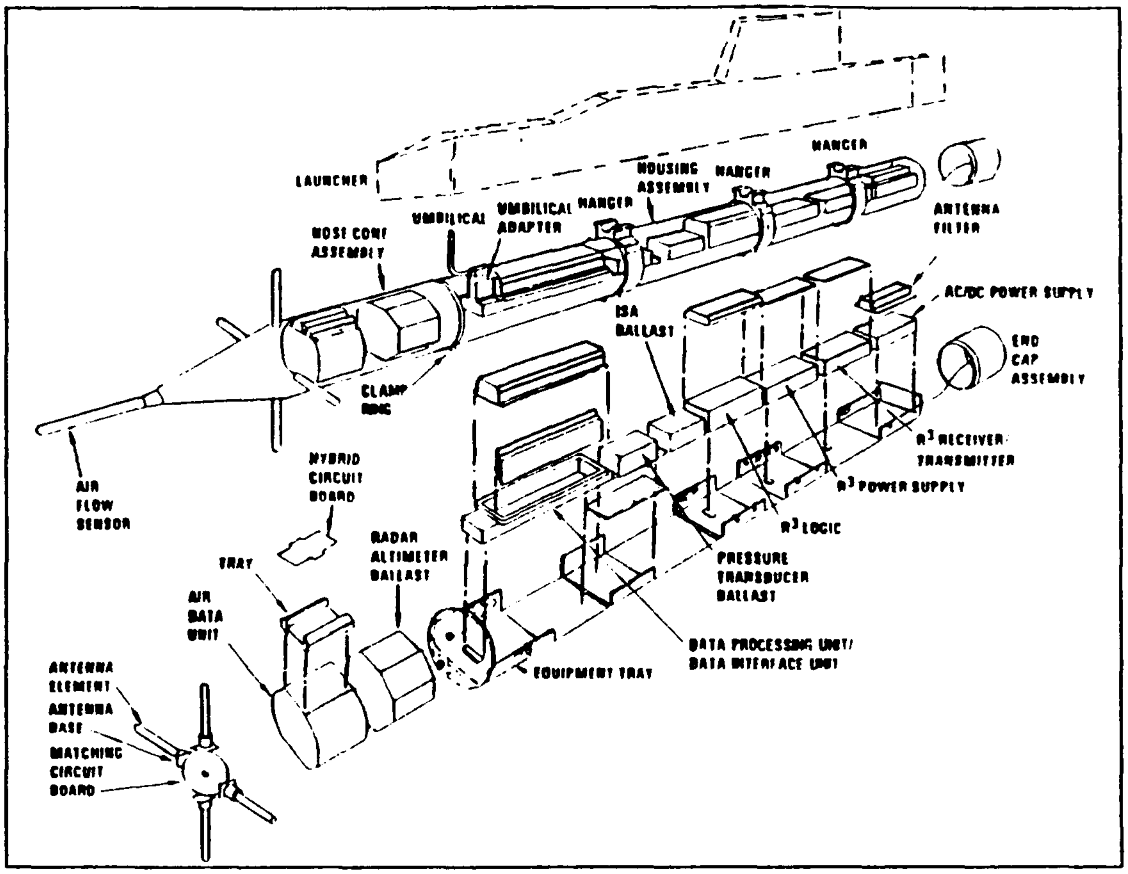

Figure 1 Service Aircraft Instrumentation Package (SAIP) [Ref. 4]

altitude of 4000 feet, and 900-1000 feet at an altitude of 10,000 feet. The tests were conducted using both first and second generation SAIPs mounted at various sites on the aircraft.

B. THESIS PURPOSE

1. To critically review the methods currently being used and those previously used to determine Cp for validity, and to verify the raw data reduction for accuracy.

2. To determine whether the pressure coefficient could be used in the EATS system evaluator program as a correction for the SAIP, and to determine an appropriate correction factor.

3. To evaluate the atmospheric model used by the EATS system, and propose a more accurate model.

II. AERODYNAMIC MODEL

A. THEORY

Altitude is determined in a pitot-static system by measuring the static pressure and relating it to the altitude through standard altitude relationships, correcting for sea level pressure and temperature. The difference between the computed altitude and the actual altitude is called position error. The greatest uncertainty in pitot-static systems is in the measurement of static pressure. The error in measuring dynamic pressure is typically small, and considered to be zero. Calibration of an altimeter is accomplished with a factor called the static pressure error. The difference between the static pressure measured at the static port and the actual static pressure is Δp. This is normalized by the dynamic pressure, q, to get the static pressure error: $\Delta p/q$. This report uses the symbol Cp when referring to the static pressure error to maintain continuity with the previous studies [Refs. 1, 2, and 3].

Figure 2, which is reproduced from Reference 5, shows the variation in Cp along the centerline of a typical subsonic aircraft. Indicated are six locations where the error is near zero; four of which would be practical for mounting a static port. These locations are still subject to position errors as is illustrated in Figure 3 which demonstrates a Mach number dependence. [Ref. 5]

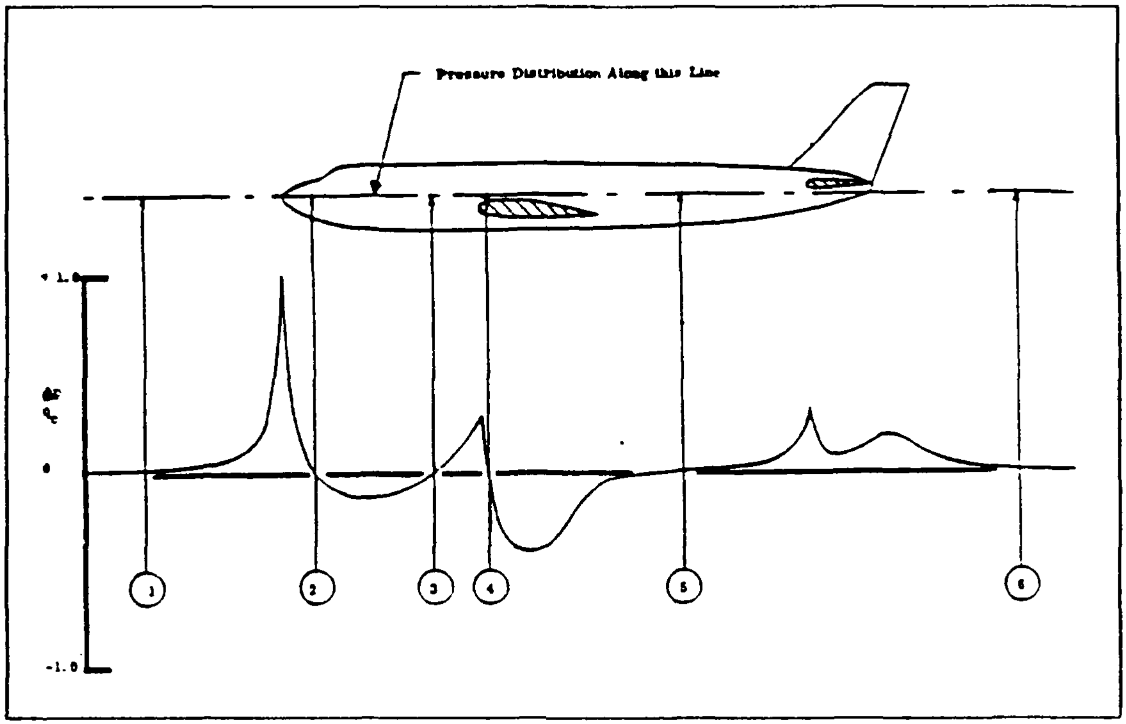

Figure 2 Cp Variations along the centerline of a typical aircraft

The pressure field under a wing is more difficult to work with since it is subject to wide variations. Figure 4 shows an example of the pressure field under a wing subject to 2-D flow [Ref. 6]. The Cp is dependent on both Mach number and angle of attack (AOA).

B. PREVIOUS ANALYSIS

In a previous study [Ref. 3], LT Rixey used several computer models to determine a pressure coefficient, Cp, for the SAIP with and without an aircraft attached. He compared

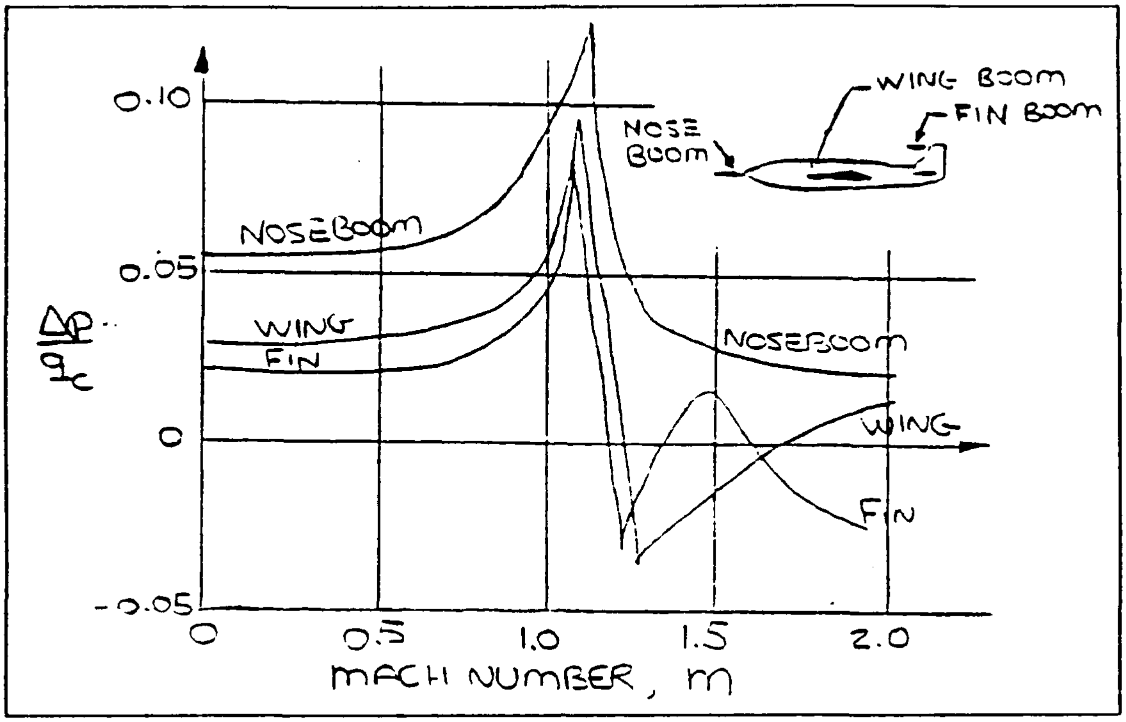

Figure 3 Variation of Cp with Mach number. Reproduced from Reference 5.

these values to Cp's computed from the data reduced by LT Eastburg [Ref. 1] using the following equation as developed in Reference 3:

$$C_p \approx -\frac{2g\Delta Z}{V_\infty^2} \tag{1}$$

Here g is the gravitational constant, ΔZ is the difference in altitude computed from the SAIP and that reported by the A-6, and V_∞ is the freestream velocity in feet/sec. After reviewing this method, it was decided to revisit the original data in order to find the most accurate means of computing the actual Cp at the SAIPs. Some causes of error in the Cp are as

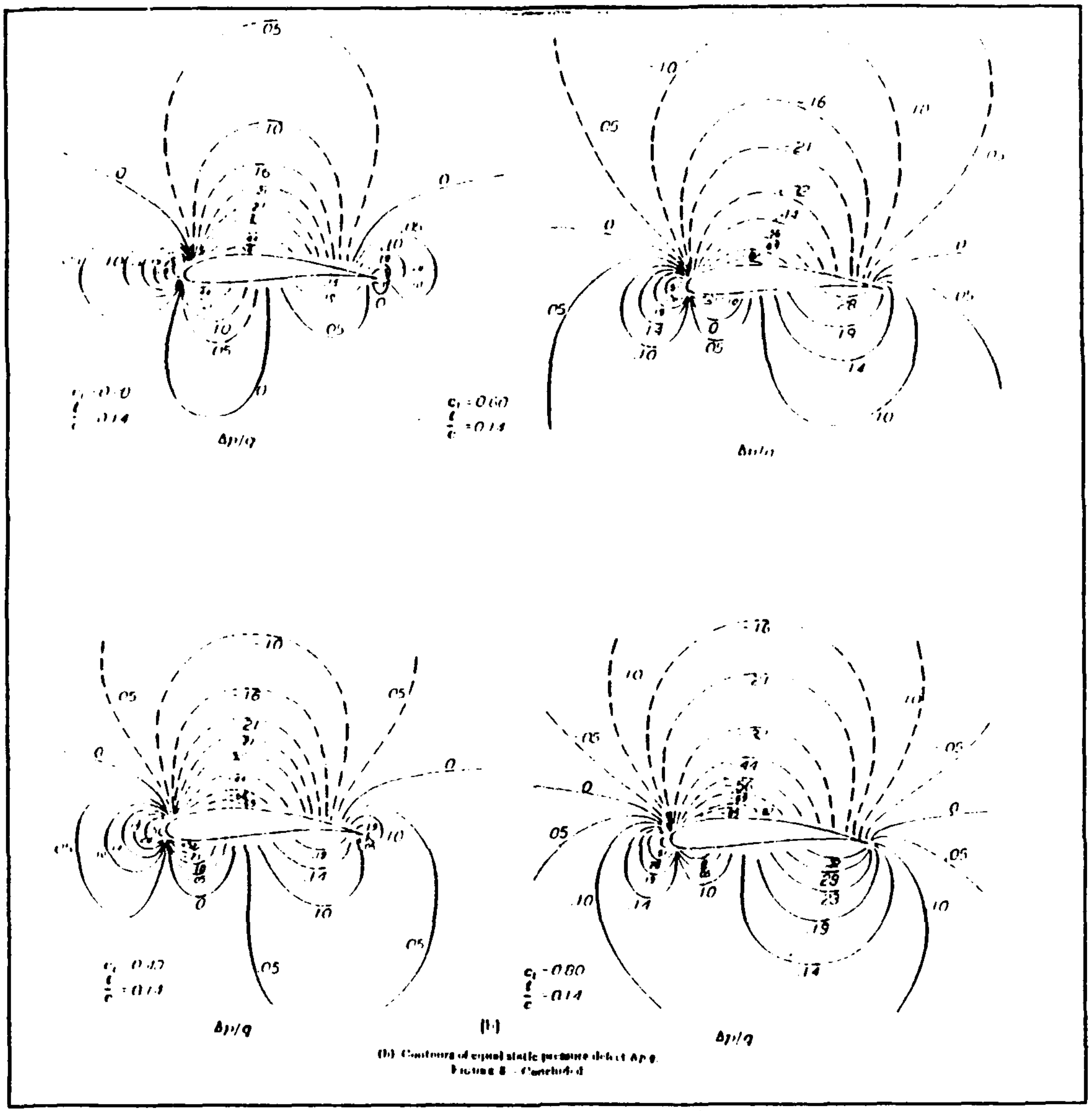

Figure 4 Pressure Field Under a Wing in 2-D Flow

follows:

1. The aircraft's velocity was taken from data in units of feet/sec, and LT Eastburg converted this to knots. LT Rixey converted the velocity back into feet/sec, and then using standard day speed of sound for 4000 feet and 10,000 feet, converted this into Mach number. Since the A-6 recorder provides Mach number directly, no conversions are in fact needed.

2. A few data points extracted by LT Eastburg did not correlate with the raw data.

3. The altitude readings used were raw altitude from the SAIP, and Processed Altitude from the A-6. These two altitudes were compared directly. It was felt that while this approach was adequate for the initial analysis, a better approach for more accurate Cp calculations is to use pressure altitude for the A-6. The primary advantage is that an exact formula is available which converts static pressure into pressure altitude. The equation assumes standard day profile. It is easily reversed to provide static pressure from the pressure altitude.

4. LT Rixey assumed the same equation was used by the SAIP and the A-6 to compute altitude. While the basic equations are the same, several of the values used are not. Actual temperature and pressure must be used in the EATS program as well as the computed gravity for 22,800 m. The A-6 Air Data Computer (ADC) uses standard day temperature and pressure (288.16K and 1013.25 mbar respectively), and standard sea-level gravity (9.806). This may have caused several problems which are discussed later.

The intention of this study is to isolate the atmospheric errors from the aerodynamic errors in the SAIP altitude readings with the goal of being able to correct the SAIP's altitude reading by accounting for these separately. A two step approach is taken. A true Cp is computed to find the aerodynamic effects, and the sounding data from the Geophysics Department at the NAWC, Pt Mugu is analyzed to determine atmospheric errors.

C. AERODYNAMIC ERROR DETERMINATION

1. Cp determination

Calculating the true Cp requires the determination of three parameters: static pressure as read by the SAIP, actual static pressure at the altitude of the aircraft, and the actual dynamic pressure. For this project, there was confidence in the latter two parameters, since they could be extracted from the A-6 air data computer printout, but only marginal confidence in the first. While the EATS system records the static pressure read by the SAIP, the static pressure was not printed out when the data analyzed for this study were taken. Unfortunately, the original tapes are no longer available, so these reading can not be established.

2. A-6 Altitude Model

The A-6 Air Data Computer (ADC) makes several corrections to the pressure reading before computing a calibrated altitude. The pressure altitude is based solely on the static pressure corrected for lag error caused by the vertical velocity [Ref. 7]. This equation is:

$$hp = 145,447*\{1-[\frac{Ps}{29.921}]^{.19026}\} \quad \textbf{(2)}$$

Where hp is the pressure altitude and Ps is the static pressure. This is the equation for a standard atmosphere using standard day temperature and pressure. By reversing this equation, static pressure is obtained as read by the A-6. Flight tests done to calibrate the A-6 static pressure reading revealed a sensitivity to vertical velocity only. This indicates a lag in the system. The correction is matched to the steady dive and pull up maneuver, as these are the two critical phases in a bombing run. The initial push over maneuver does not match the correction curve as closely. For the data in this study, the vertical velocity is relatively low, so the error in static pressure can be assumed sufficiently low as well [Ref. 9].

The dynamic pressure is computed from the Mach number measured by the A-6 with the equation:

$$q = \frac{\gamma}{2} P_\infty M_\infty^2 \qquad (3)$$

P_∞ is the static pressure computed with Equation 2, γ is the specific heat of air, and M_∞ is the freestream Mach number.

3. SAIP Altitude Model

The static pressure read by the SAIP during the flight tests cannot be extracted with certainty given the data available. There are too many factors required to back out the static pressure that presently are not available. To accurately evaluate the aerodynamic factors and to generate a Cp correction, data will have to be used from more recent runs for which all of these factors, or the raw static pressure, are available.

a. Atmospheric model

The EATS altitude model assumes a standard altitude profile, however measured pressure and temperature values are used [Ref. 8]. The temperature and pressure are measured at two locations: GIS located at San Nicholas Island, elevation 260.727 m, and MOCS located at Pt. Mugu Ca, elevation 4.17 m.

San Nicholas Island is located off the coast approximately 70 miles from Pt. Mugu in the middle of the test range. The temperature and pressure measurements are read into the 3003 and 3008 records of the EATS systems evaluator program, respectively. The 3007 record indicates which location of data was used for the test. The temperature is converted to sea level temperature using the standard lapse rate, β, of 0.0065 °C/m. Likewise the pressure is converted to sea level pressure using the standard day profile equation:

$$P_{sl} = P_{sf}\left(1 + \frac{\beta h}{T_{sf}}\right)^{\frac{g_{ave}}{\beta R}} \tag{4}$$

Where:
P_{sl} is the sea-level pressure
P_{sf} is the pressure read
β is the temperature lapse rate
h is the altitude of the reading
T_{sf} is the temperature read
g_{ave} is the gravity at 22,800 meters
R is the specific gas constant

Since none of these records were printed out, assumptions had to be made as to their actual values. The only available data to estimate these parameters are the sounding data recorded by the Geophysics Department at Pt Mugu. Soundings for 7 November, 1989 were taken at 1404Z, 1729Z, and 2152Z, at Pt Mugu, and at 1258Z, 1550Z, and 1951Z at San Nicholas Island. Using the Pt Mugu 2152Z reading, the pressure was taken to be 1010.7 mbar, and the temperature was taken to be 19.0°C. If the 1951Z reading from San Nicholas Island were used instead, the temperature and pressure would be 16.7°C and 1012.8 mbar respectively. The San Nicholas Island sounding data would have to be interpolated between 45 feet and 1000 feet to get a reading for 260 meters (855.4 feet). The Pt Mugu sounding data on the other hand, has a reading for 7 feet, which is sufficiently close to the reading at 4 meters (13 feet). For this reason, the Pt Mugu values will be used. The inability to ascertain the actual values used for these two parameters remains the largest source of error in this study.

b. Sensitivity to Variations of Initial Parameters

To determine the magnitude of error possible due to the uncertainty in the pressure and temperature used, a comparison was done to show how the Cp varied in relation to the initial conditions. The static pressure was determined from the A-6 pressure altitude as *described above*. The pressure read by the SAIP was reduced by using the equation from the EATS system evaluator program:

$$H = \frac{T_{sl}}{\beta}\left[1 - \left(\frac{P}{P_{sl}}\right)^{\frac{\beta R}{g_{ave}}}\right] \tag{5}$$

where H is the geopotential altitude and P is the static pressure read by the SAIP. This equation is reversed to give:

$$P = P_{sl}\left(1-\frac{\beta H}{T_{sl}}\right)^{\frac{g_{ave}}{\beta R}} \tag{6}$$

Figure 5 demonstrates how the Cp changes when the sea level temperature is varied by only five degrees centigrade, and Figure 6 shows what happens when sea level pressure is varied only by 10 mbar.

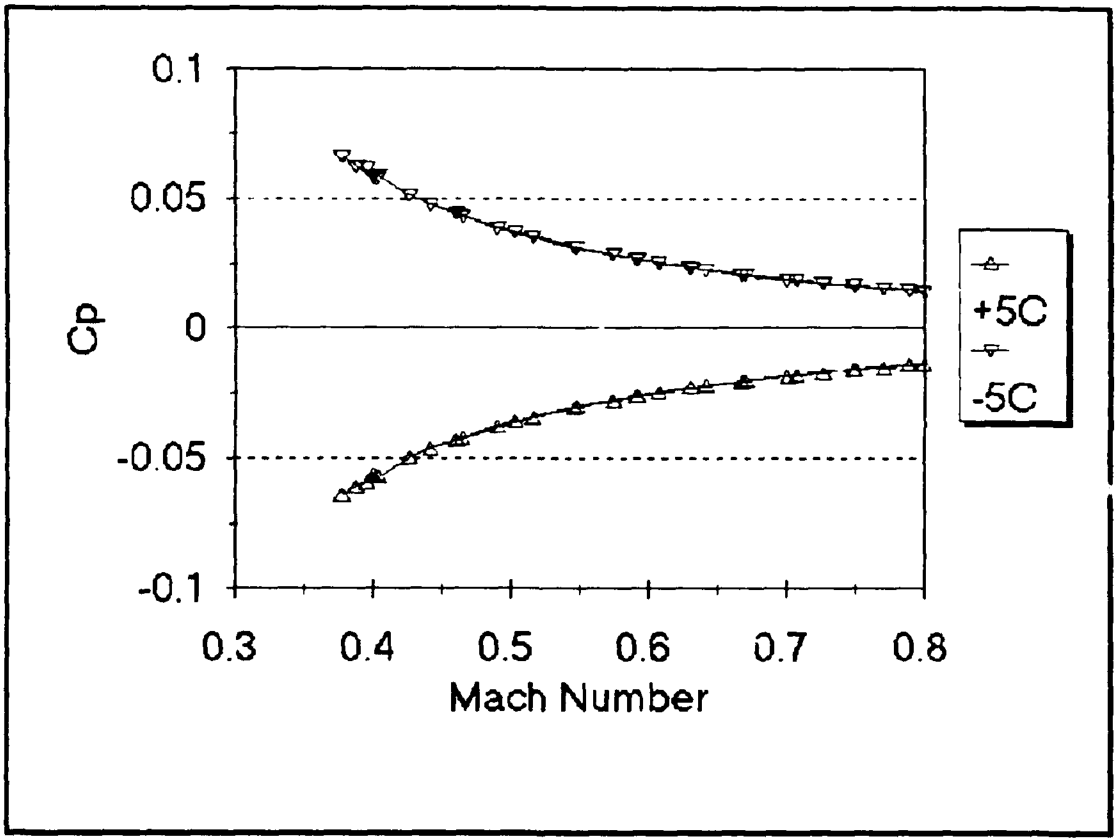

Figure 5 Variation in the Cp due to changing the assumed temperature input for Run 3, inboard mounted SAIP, 10,000 ft

In both cases the Cp is effected dramatically. The variation is of the same magnitude as the total computed Cp. The sounding data indicate that the atmospheric model used in the EATS is off by about 200 feet at an altitude of 10,000 feet depending on the initial conditions were used. The other 400 to 1000 feet of the error along with the variation in the altitude error is attributed to the aerodynamics.

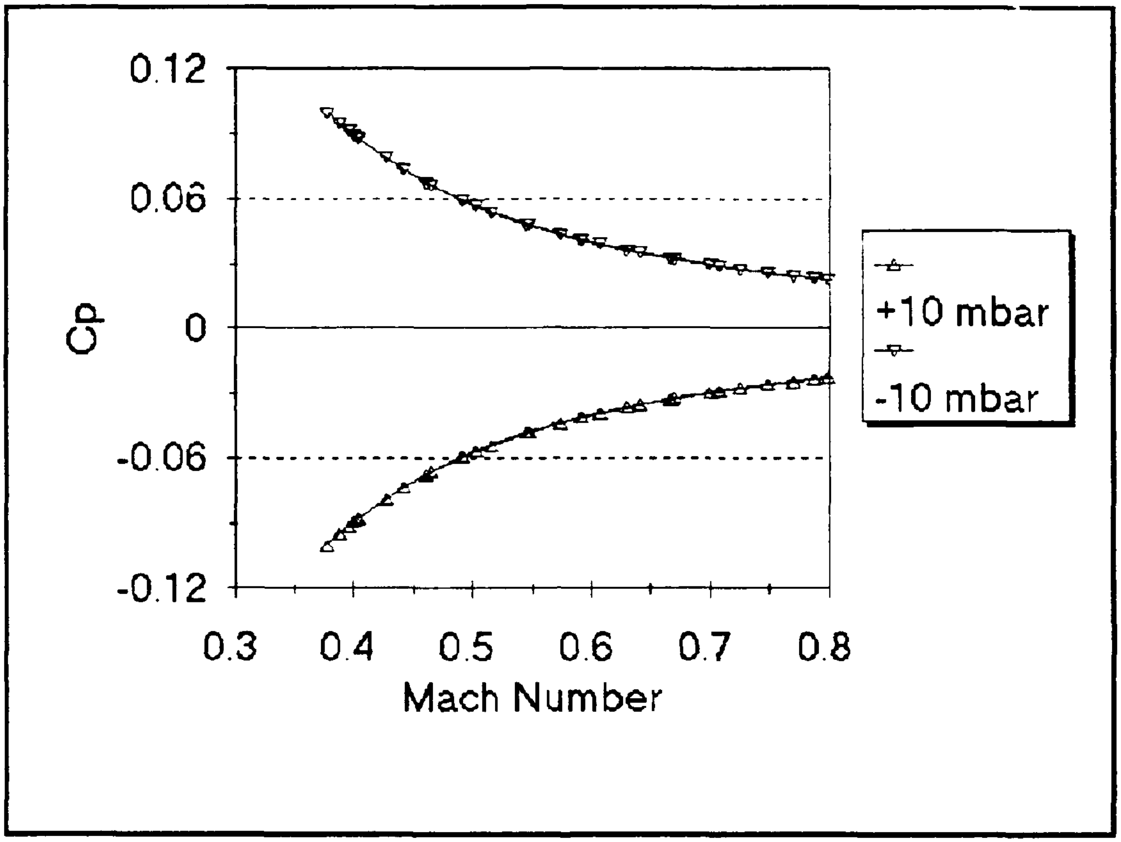

Figure 6 Variation in Cp due to changing the assumed pressure input for run 3, inboard mounted SAIP, 10,000 ft

D. AERODYNAMIC CORRECTION

Having defined the limitations and assumptions noted above, the study proceeds as follows: The static pressures are computed for the A-6 and the SAIPs, and converted into Cp. Several methods are used to fit the data in order to define Cp as a function of Mach number. These include linear, exponential, logarithmic and power curve fits. The best correction turns out to be the quadratic fit. The SAIP pressure is then entered into the altitude equation used by the A-6 to determine the error due to the aerodynamics alone. The altitude equation assumes that static pressure is being read. The static pressure error factor can be rearranged as follows:

$$P_\infty = \frac{P_{SAIP}}{\frac{\gamma}{2} M_\infty^2 C_p + 1} \tag{7}$$

Using a quadratic estimate for Cp gives:

$$P_\infty = \frac{P_{SAIP}}{\frac{\gamma}{2} M^2 (A*M^2+B*M+C)+1} \tag{8}$$

Where A, B, and C are the coefficients for the quadratic fit of Cp. The correction then becomes a function of Mach number only. Although the Cp is actually a function of both Mach number and angle of attack (AOA), using the Mach number alone appears to give adequate results.

This correction for P_∞ keeps the altitude error below 100 feet. Figure 7 illustrates the improvement in altitude reading for Run 3. The upper curve shows the error using no correction for Cp, while the lower curve uses a quadratic correction. The remainder of the runs are shown in Appendix B. The data for each SAIP location and altitude were fit to a corresponding correction curve:

10,000 feet Inboard: $0.6796M^2 - 0.9356M + 0.3906$

10,000 feet Outboard: $0.1875M^2 - 0.2392M + 0.1429$

4,000 feet Inboard: $0.3393M^2 - 0.4251M + 0.1906$

4,000 feet Outboard: $0.1239M^2 - 0.1077M + 0.0706$

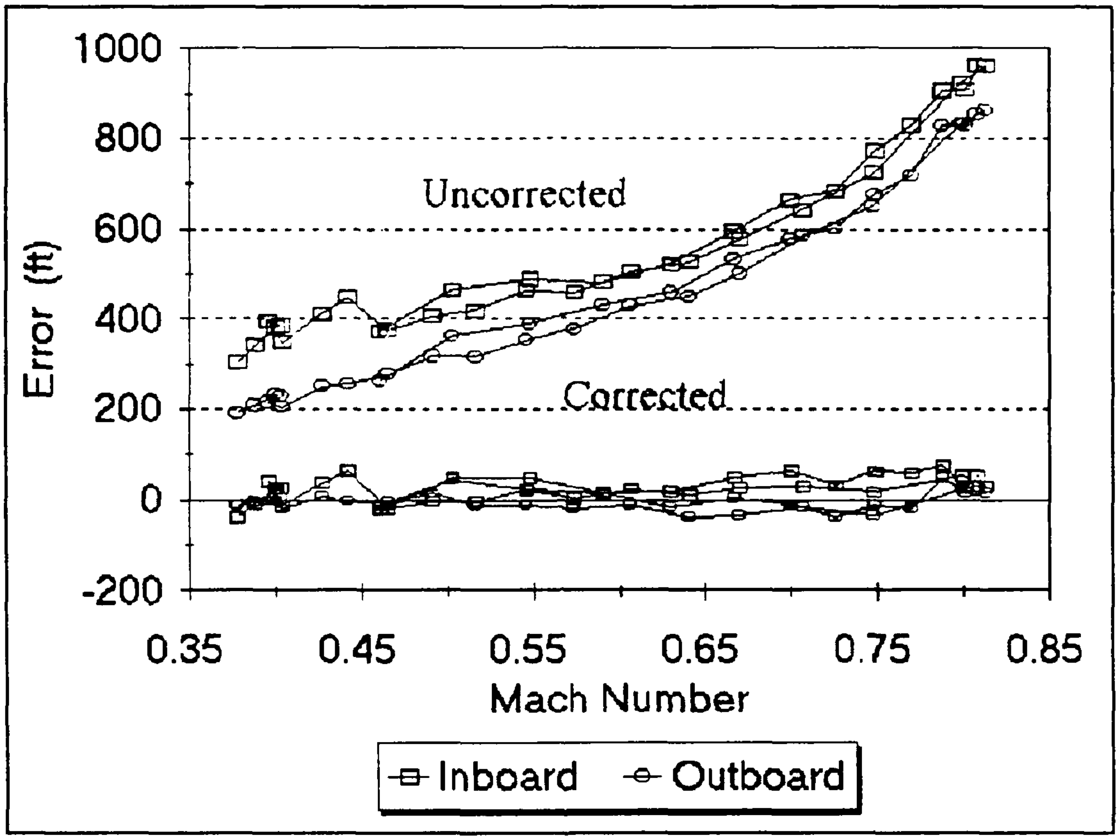

Figure 7 The altitude errors for Run 3 with and without a quadratic approximation for Cp to correct P_∞, 10,000 feet

The curve for 10,000 feet inboard SAIP location is shown in Figure 8. The remainder of the curves are plotted in Appendix B. While these curves produced adequate results for this study, further flight testing is required to extend the data base for other aircraft and other altitudes.

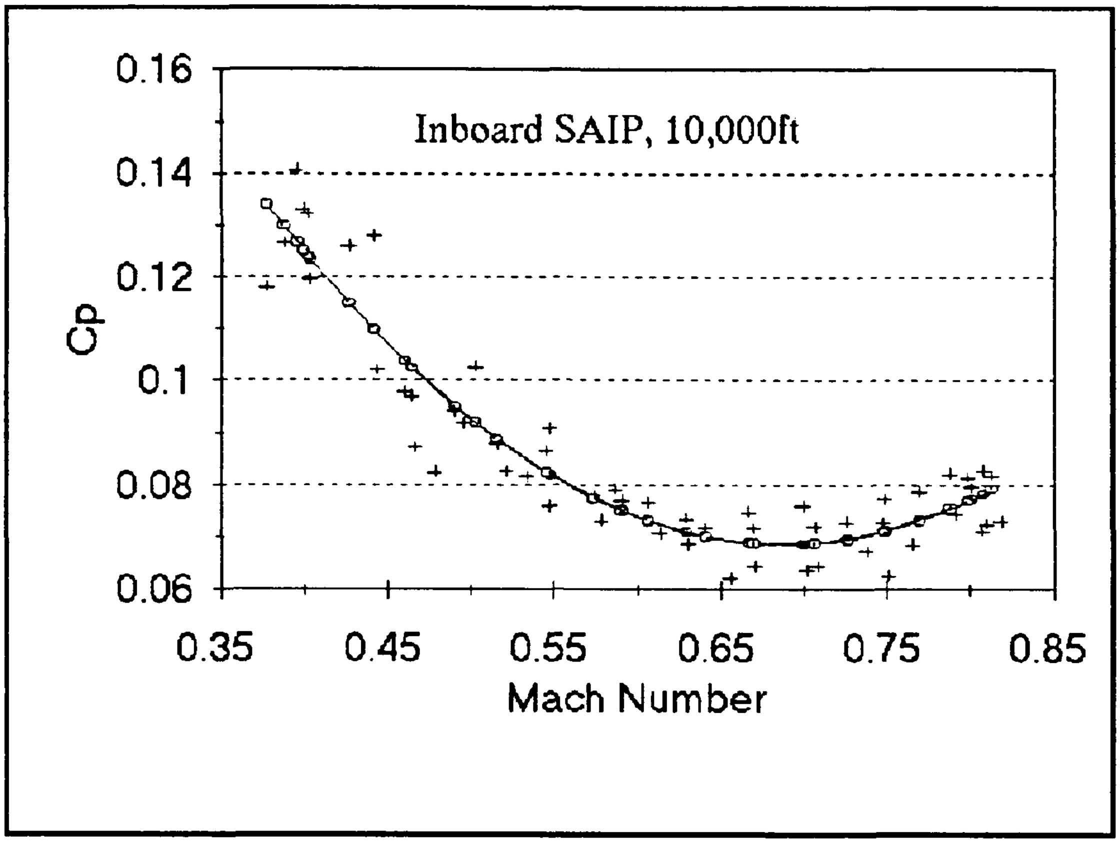

Figure 8 The Cp Correction Curve for the SAIP located at the Inboard pylon flying at 10,000 ft

III ATMOSPHERIC MODEL

A. THEORY

The EATS system evaluator program uses the standard atmospheric model. The derivation of this model begins with the hydrostatic equation which balances the forces on a column of air:

$$\frac{dP}{dz} = -\rho g \tag{9}$$

This assumes that the change in the pressure force must equal the weight of the air. The minus sign is used since dP/dz is always negative. By substituting for ρ using the perfect gas law:

$$\rho = \frac{P}{RT} \tag{10}$$

gives:

$$\frac{dP}{dz} = -\frac{Pg}{RT} \quad or \quad \frac{dP}{P} = -\frac{g}{RT}dz \tag{11}$$

To solve this equation a fictitious altitude, called the geopotential altitude, H, has been defined as the equivalent altitude assuming a fixed gravity constant:

$$g_o dH = g dz \tag{12}$$

where g_o is the standard sea-level gravity. The U. S. Standard Atmosphere defines the temperature schedule as shown in

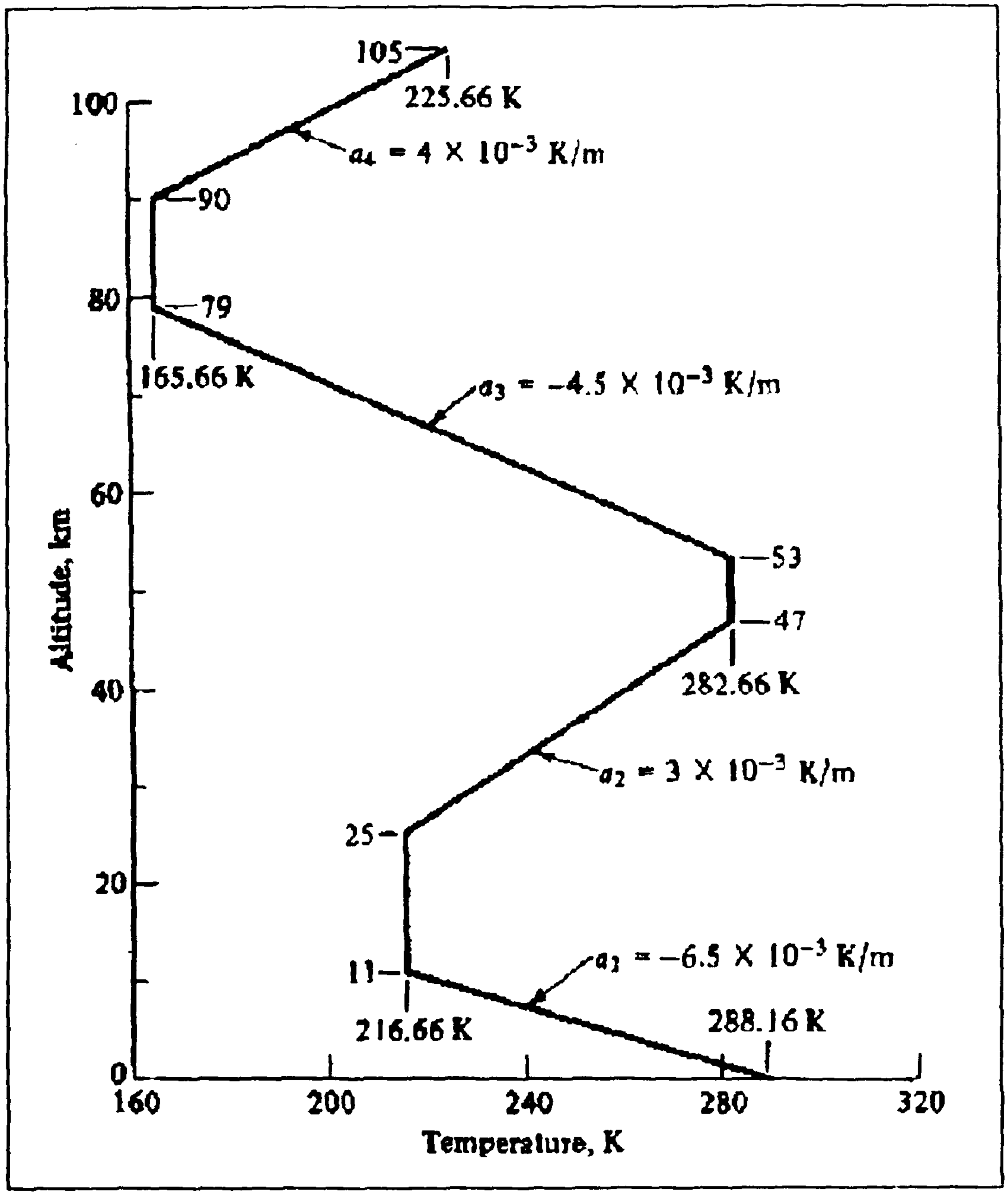

Figure 9 The U. S. Standard Atmosphere Temperature Profile

Figure 9 [Ref. 10]. For this study only the first two regions will be looked at. The troposphere assumes a constant lapse rate, β, of 0.0065 °C/meter up to 11 kilometers (36,000 feet), and the isothermal region of the stratosphere assumes a constant temperature up to 25 kilometers (82,000 feet). Therefore the temperature can be expressed as $T = T_o - \beta H$. Substituting this and equation 12 into equation 11 and taking the integral gives:

$$\int_{P_o}^{P} \frac{dP}{P} = -\int_{0}^{H} \frac{g_o}{R(T_o - \beta H)} dH \qquad (13)$$

integrating yields:

$$\ln \frac{P}{P_o} = \frac{g_o}{\beta R} \ln\left(\frac{T_o - \beta H}{T_o}\right) \qquad (14)$$

solving for P:

$$P = P_o\left(1 - \frac{\beta H}{T_o}\right)^{\frac{g_o}{\beta R}} \qquad (15)$$

or rearranging for altitude:

$$H = \frac{T_o}{\beta}\left[1 - \left(\frac{P}{P_o}\right)^{\frac{\beta R}{g_o}}\right] \qquad (16)$$

Above 11 kilometers, in the isothermal region, temperature is assumed to be a constant $T_{iso} = T_c - 71.5°$. The altitude is then computed by:

$$H = -\frac{RT_{iso}}{g_o}\ln\frac{P}{P_{iso}} + 11,000 \qquad (17)$$

with P_{iso} being the pressure at the beginning of the isothermal region.

B. EATS ALTITUDE MODEL

The EATS system evaluator program takes the standard atmosphere profile developed previously, and enters in the current pressure and temperature. As described in Chapter II, these readings come from two sites: San Nicholas Island and Pt. Mugu. The program then determines which of the two readings it will use, and converts the values to sea-level values using the same standard atmosphere profile previously described. The only difference is that the EATS system uses a value g_{ave} instead of g_o which is the computed gravity at an altitude of 22,800 meters (approximately 9.725 for g_{ave} compared to 9.806 for g_o) [Ref. 8]. While there is no documentation explaining why this is done, a comparison of the error experienced by varying the gravity term demonstrated better accuracy with a smaller value for g_o. This is shown in Figure 10 which plots the error versus altitude using three different values for g_o. While the error with g_o equal to 9.725 is still significant, it is typically within the 3% error specification up through 60,000 feet. Depending on the severity of the inversion layer, this correction can still fall well outside the specification limit. On days where there is no significant inversion layer, all three curves remain within the 3% window.

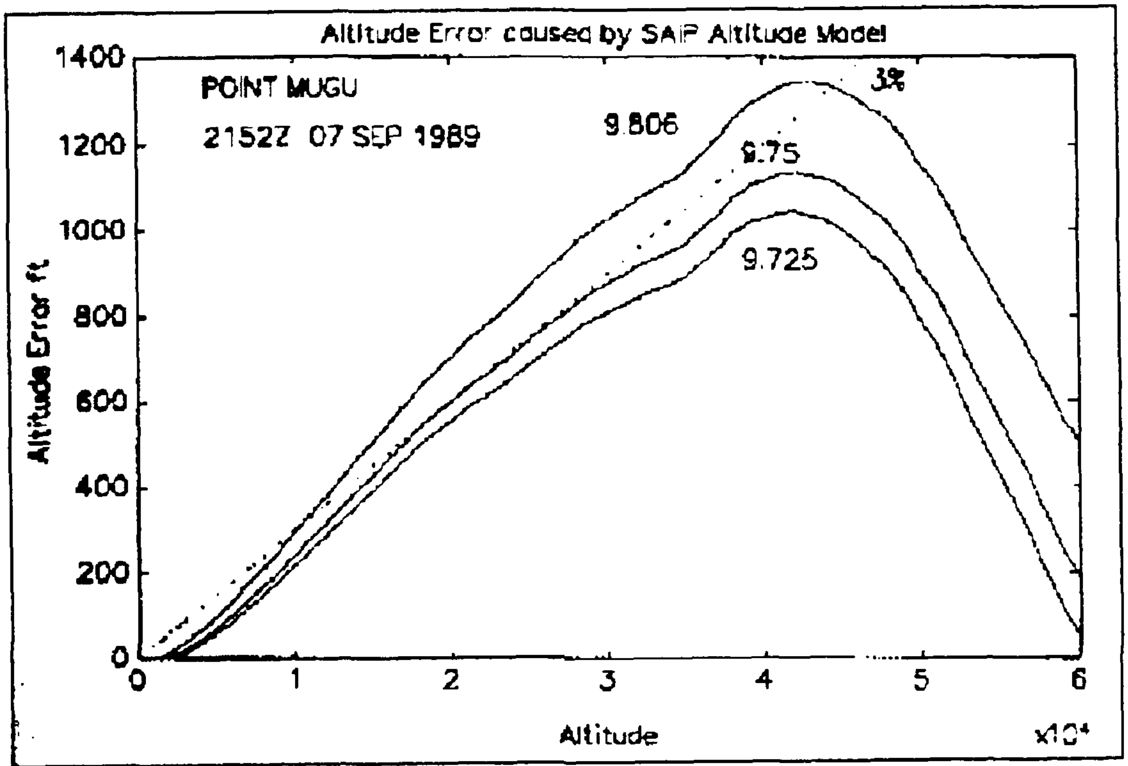

Figure 10 The Effect on Altitude Error of Varying g_o

C. **ALTITUDE ERRORS OF EATS MODEL**

The main problem with the standard atmosphere model is that it does not take into account the severe inversion layers that are prevalent at Pt Mugu. Although only minor altitude errors occurred (1000 feet at an altitude of 45,000 feet) on days showing a standard temperature profile , virtually every sounding examined was non-standard. Without examining the profile, there is no way of knowing how severe the errors will be. Most days there was an inversion layer profile. The temperature decreases steadily until an altitude of about 1,000 feet. The temperature suddenly jumps 10°C and then decreases steadily until it hits the isothermal region. Also it is not uncommon for the isothermal region to start at 50,000 feet, which is considerable higher than the standard 36,000 feet. Another profile started with a positive lapse rate for the first few thousand feet, and then the temperature decreased steadily giving only three regions. Figures 11 and 12 show some typical temperature profiles with the corresponding errors in altitude predictions. The model typically predicts well until an inversion layer is encountered, then the altitude error jumps to 800-1,400 feet at an altitude of 30,000 feet. Above 60,000 feet, the altitude error can exceed 3,000 feet.

D. METHODOLOGY TO CORRECT EATS MODEL

Several methods were attempted to bring the atmospheric model within specifications. All the methods bring the estimate closer than the current model, but all required operator intervention.

This investigation built on the work of Mr. Anthony A. Terrameo, Jr. of NAWCWPNS, Pt. Mugu [Refs. 11 and 12]. The atmospheric model proposed by Mr. Terrameo in these reports corrects the errors due to the inversion layer, and provides

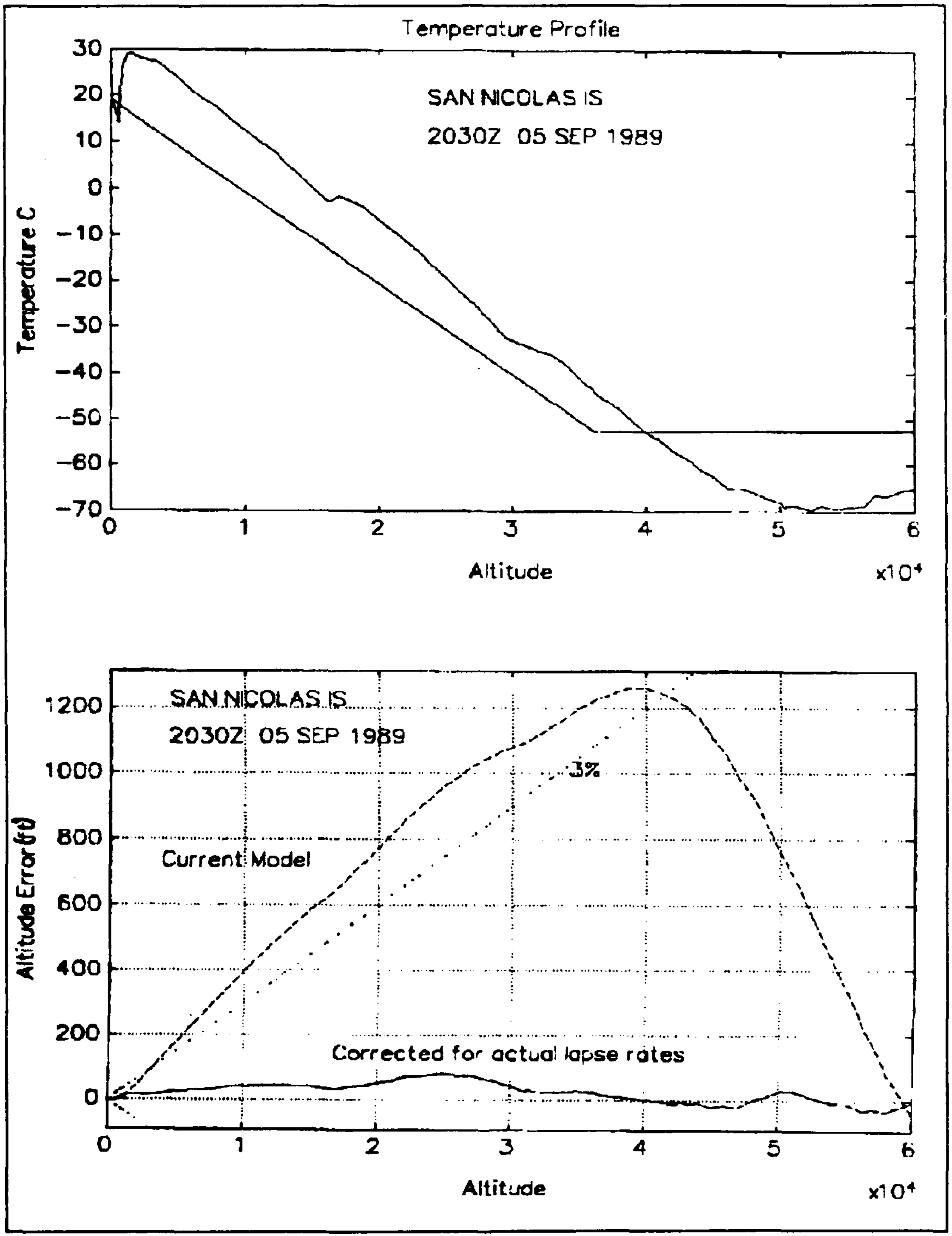

Figure 11 Typical Temperature Profile for the Pt. Mugu Area Compared to Standard Temperature Profile Along With the Altitude Errors Caused by the Inversion Layer and the Errors With a Corrected Model

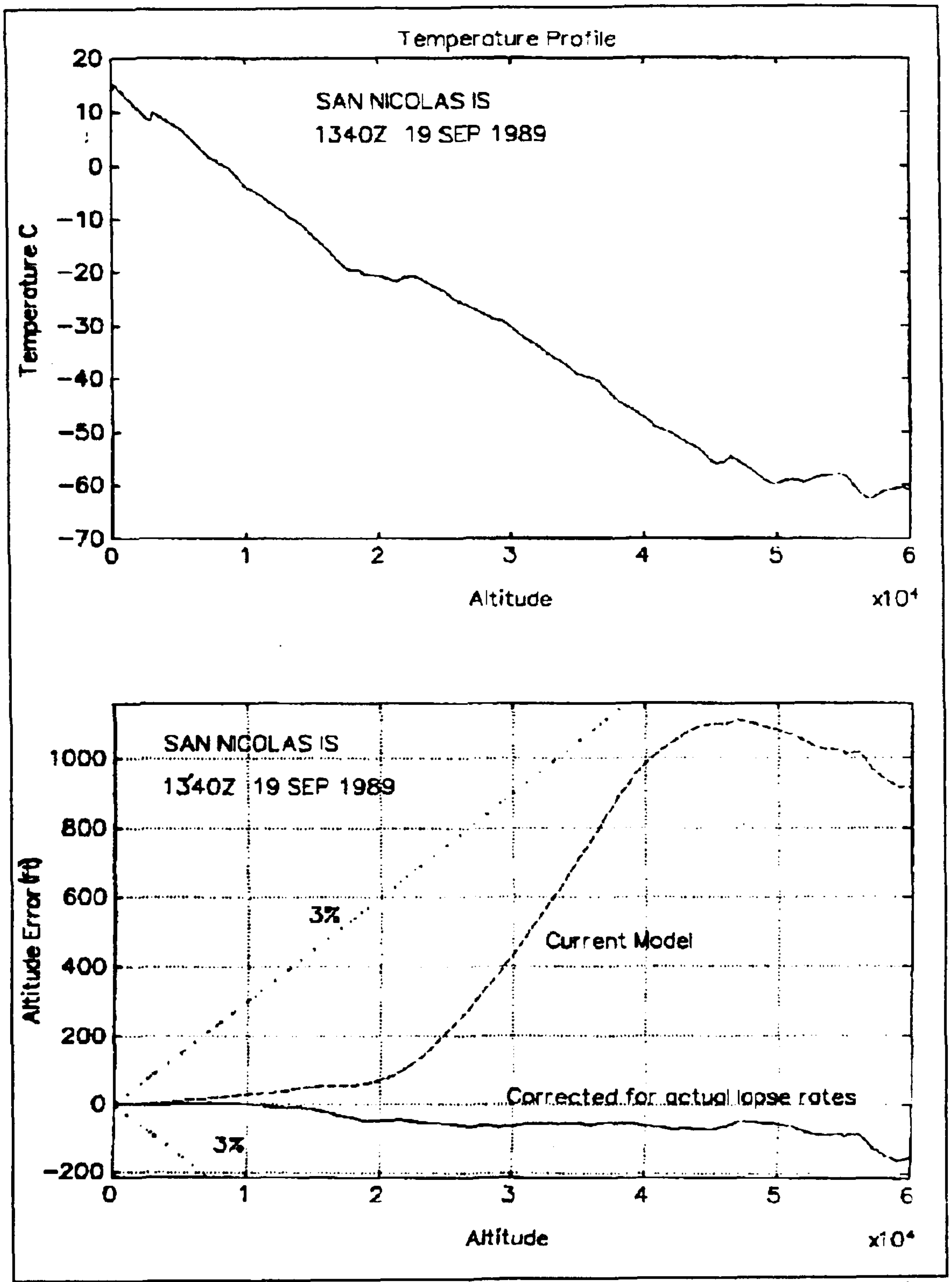

Figure 12 A Temperature Profile with only a Mild Inversion Layer and the Altitude Errors it Causes.

an accurate profile for altitude. The benefit of the methods presented here is reduced computation time at the expense of increased operator involvement.

The foundation for all the methods developed here is to divide the atmosphere into a four section model and compute actual lapse rates for temperature based on the sounding data provided by the Geophysics Department at NAWCWPNS, Pt. Mugu. The first region extends from the earth's surface to the bottom of the inversion layer. The second region covers the inversion layer. The third region stretches from the top of the inversion layer to the isothermal region. The final region covers the isothermal layer. Sounding data must be examined to define these regions. The temperature and pressure at each transition point is recorded, and the lapse rate is determined by linear regression for each section.

The first model uses the measured temperature and pressure and the computed lapse rates as follows: The regions are defined by the pressure, and an altitude is computed for each transition point. To determine which region the aircraft is in, and which equation to use, the pressure read from the SAIP is compared to the pressure read at each transition point. Each equation uses the temperature and pressure measured at the beginning of the region, and the lapse rate for the region. The altitude computed by the equation is added to the altitude computed for the bottom of the region to determine the total altitude. The third program in Appendix A demonstrates how this was accomplished using MATLAB. This worked very well for most days to bring the error down from over 1,400 feet to under 250 feet at an altitude of 30,000 feet. The method does require the sounding data to be <u>manually examined</u> to pick out the layer. When a program was written to do this automatically, several temperature profiles would fool the program into making the wrong breaks. A more sophisticated program could possibly work more effectively, but manual intervention will still likely be required.

The locations chosen for the transition points has a large effects on the errors in the model. Depending on where the layer was placed, the error would vary from under 100 feet up to 600 feet. This can be seen by comparing the correction shown in Figure 13 to the correction in Figure 12. The only difference between the two figures is the definition of the temperature regions. For Figure 12, the breaks are at: 15,000, 23,000 and 50,000 feet. Figure 13 used altitude breaks of: 5,000, 5500, and 50,000 feet. The second and third programs in Appendix A plot the temperature profile so the altitude breaks for each section can be entered. An iteration process is used to achieve an optimum profile. This method did not work particularly well with profiles with only three distinct sections, but it could easily be rewritten to accommodate this. The lower graphs in Figures 11 and 12 demonstrate this correction method.

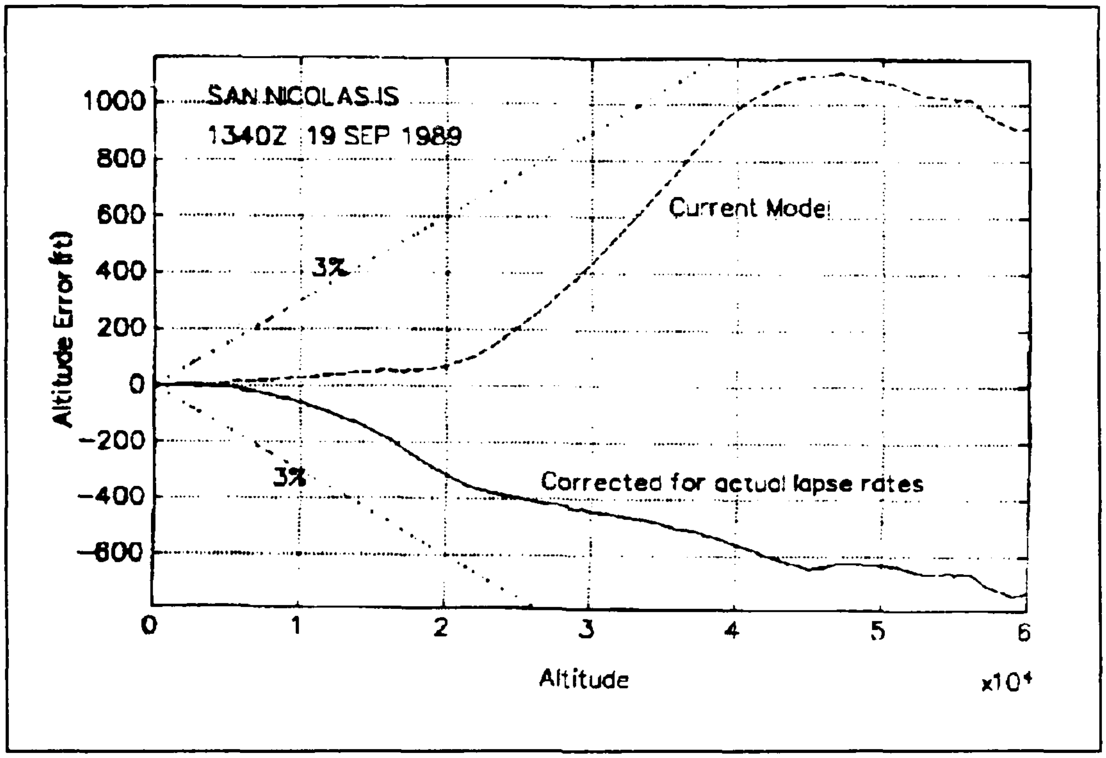

Figure 13 The altitude error for a corrected atmospheric model using the wrong transition points.

One profile caused significant problems. It consisted of a large jump in temperature at the surface, and then proceeded with a standard inversion layer profile. It was assumed that the first datum point in the sounding was bad. The method worked fine after the surface temperature reading was altered to fit a four section profile.

The next method is identical to the above, except that both pressure and altitude are used to define each section. Instead of using a computed altitude added to each section, the actual altitude for that region, as recorded from the sounding data is used. This has the advantage of bringing the error to zero at the beginning of each section. Unfortunately, this profile has considerable discontinuities, which cause the altitude to jump as the aircraft passes through each transition layer.

A third method computes the gravity constant for the average altitude in each region. This gravity term is used in each equation, and true altitude is produced rather than geopotential altitude. This method worked well, but did not produce any better accuracy than the first method. The advantage is in computational time. The gravity term is computed once, while in the other methods geopotential altitude must be converted into true altitude for each reading. Figure 14 shows the result of this method which reduced the error from 1,100 feet to under 150 feet.

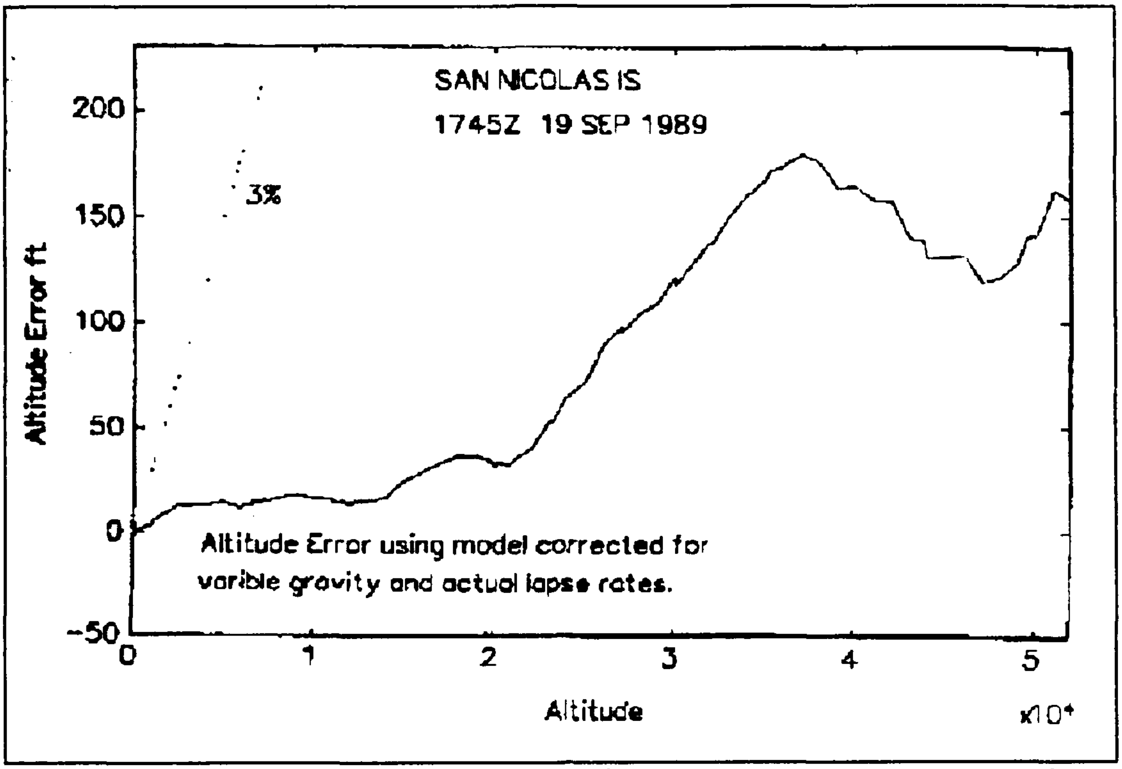

Figure 14 The Altitude Error Using True Lapse Rates and an Average g_o for each region.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study evaluated the possibility of correcting the altitude determination error of the SAIP by using Cp to correct the aerodynamic errors and using a modified atmospheric model to correct for the effects of the inversion layers experienced at Pt. Mugu. It was demonstrated that this combination is a viable solution to the SAIP's altitude problems.

Assuming that Cp is a function of Mach number alone gives errors under 100 ft for all velocities from Mach 0.4 to Mach 0.8. Changing the atmospheric model for the conditions at Pt. Mugu by incorporating the sounding data from the Geophysics Department at NAWCWPNS, Pt. Mugu will allow the EATS system evaluator program to determine the actual altitude to within 200 ft up through an altitude of 60,000 ft. The Geophysics Department has indicated that the soundings can be scheduled for any event, and data can be reduced and sent to the EATS center within two hours of the data being taken. Both corrections are simple to add to the current program, and effectively correct the altitude problems with a minimum of expense, since no hardware modifications are required. More flight test data must be reduced for the Cp correction curves, but the method is straightforward. Although the Cp was computed as a function of mach number and altitude, the data also displayed a definite dependence on either AOA or vertical velocity. Either could be added into the equation for a better fit.

B. RECOMMENDATIONS

The atmospheric model should be modified promptly to more accurately predict altitude. The correction to the software is relatively simple, and there would be no increase in the real time computing. A program must be written to view the temperature profile received from the Geophysics Department, and to plot the altitude error so the best profile can be entered. Rather than using several models and selecting the best model for the day, one model that can accommodate several regions using the actual lapse rates would be adequate, and much easier to fit to any temperature profile.

The aerodynamic correction will not be as straightforward. Implementing the correction once it is determined is easy; determining the correction is not. Any flight measurement could be used which has raw pressure, Mach number, altitude, and vertical velocity or AOA available. The data must be analyzed to determine Cp as a function of mach number, and altitude. Vertical velocity or AOA could be added depending on which is more readily available to develop a better correction curve. If no data exists with these parameters, then future flight tests must be set up to extract this information.

The SAIP could still be a viable altitude determining resource if these corrections are implemented. Although the geopositional satellite system (GPS) is to be implemented in the future, the SAIP is likely to be in use for the next several years.

APPENDIX A: MATLAB PROGRAMS

A. PROGRAM TO SHOW EFFECT OF VARYING g_{ave}.

This program varies the gravity term used in the EATS equation to show the effect of using the g_{ave} value for 22,800 meters. All of the equations here are in a single line in the actual program, but have been split into two lines here when necessary.

```
  % This program takes an input file of the sounding data, and
  % plots it using three values for gave.

A=size(HTP);                         % HTP is the sounding data
H=[];                                % (Height, Temperature,
HG=[];                               %  Pressure)
M2F=3.28083989501;                   % Conversion for meters to feet
Rad=6348407*M2F;                     % Earths radius as supplied by
Rad1=6348407*M2F*9.80665/9.795707;   % Geophysics Dept.
Gave=9.806; G='9.806';
Tu=HTP(1,2)+273.15 - 0.0065*(11000-HTP(1,1)/M2F);
Pu=HTP(1,3)*(1-((.0065*(11000-HTP(1,1)/M2F))/
    (HTP(1,2)+273.15)))^(Gave/1.86576);

for I=1:A(1),
  if HTP(I,3)>Pu,
     H(I,1)=((HTP(1,2)+273.15)/.0019812)*(1-(HTP(I,3)/
            HTP(1,3)).^(1.86576/Gave))+HTP(1,1);
  else,
     H(I,1)=-(M2F*287.04*Tu/Gave)*(log(HTP(I,3)/Pu)) +
            11000*M2F;
  end;
end;
HG=Rad*H./(Rad1-H);
ERROR=HTP(:,1)-HG;

plot(HTP(:,1),HTP(:,2))
title('Temperature Profile')
xlabel('Altitude')
ylabel('Temperature C')
gtext('')
```

```
plot(HTP(:,1),ERROR)
xlabel('Altitude')
ylabel('Altitude Error ft')
title('Altitude Error caused by SAIP Altitude Model')
gtext(NAME)
gtext(DATE)
gtext(G)

Gave=9.75;G='9.75';
Pu=HTP(1,3)*(1-((.0065*(11000-HTP(1,1)/M2F))/
   (HTP(1,2)+273.15)))^(Gave/1.86576);

for I=1:A(1),
  if HTP(I,3)>Pu,
     H(I,1)=((HTP(1,2)+273.15)/.0019812)*(1-(HTP(I,3)/
            HTP(1,3)).^(1.86576/Gave))+HTP(1,1);
  else,
      H(I,1)=-(M2F*287.04*Tu/Gave)*(log(HTP(I,3)/Pu)) +
             11000*M2F;
  end;
end;


HG=Rad*H./(Rad1-H);
ERROR=HTP(:,1)-HG;
hold;
plot(HTP(:,1),ERROR)
gtext(G)

Gave=9.725;G='9.725';
Pu=HTP(1,3)*(1-((.0065*(11000-HTP(1,1)/M2F))/
   (HTP(1,2)+273.15)))^(Gave/1.86576);

for I=1:A(1),
  if HTP(I,3)>Pu,
     H(I,1)=((HTP(1,2)+273.15)/.0019812)*(1-(HTP(I,3)/
            HTP(1,3)).^(1.86576/Gave))+HTP(1,1);
  else,
    H(I,1)=-(M2F*287.04*Tu/Gave)*(log(HTP(I,3)/Pu)) +
           11000*M2F;
  end;
end;
HG=Rad*H./(Rad1-H);
ERROR=HTP(:,1)-HG;
plot(HTP(:,1),ERROR)
gtext(G)

plot(HTP(:,1),HTP(:,1)*.03,'.')
gtext('3%')
meta graph1
hold;
```

B. PROGRAM TO PLOT ALTITUDE ERROR USING A VARIABLE g_{ave}

This program computes an average g_{ave} for each section of the atmosphere and uses that to calculate actual altitude, instead of using a single g_{ave} and then converting the geopotential altitude into actual altitude. The input file of the sounding data is analyzed to break up the atmosphere into four sections, and the gravity for the average altitude for each section is computed. Due to the great variance that can be seen in temperature profiles, the data has to be examined manually.

```
  M2F=3.28083989
A=size(HTP);
T0=HTP(1,2)+273.15;
P0=HTP(1,3);
H0=HTP(1,1);
R=287.04;
GSL=9.7957;
H=[];
P3=0;
RAD=20820807;
axis([0,5000,0,30]);
temp                       % temp is a program to plot the
axis;                      % temperature profile, so the altitude
temp                       %  breaks can be determined.
HT=input('enter the altitude breaks: ');

TEST=1;                   % The breaks are determined, and
for I=1:A(1),             % constants initialized
  if TEST==1,
     if HTP(I,1)>HT(1) & HTP(I,2)<HTP(I+1,2),
        T1=HTP(I,2)+273.15;
        P1=HTP(I,3);
        H1=HTP(I,1);
        B=polyfit(HTP(1:I,1),HTP(1:I,2),1);
        B0=-B(1);
        TEST=2;
        B=I;
```

```
        G1=GSL*(RAD^2/(RAD+H1/2)^2);
     end
  elseif TEST==2,
     if HTP(I,1)>HT(2) & HTP(I,2)>HTP(I+1,2),
        T2=HTP(I,2)+273.15;
        P2=HTP(I,3);
        H2=HTP(I,1);
        B=polyfit(HTP(B:I,1),HTP(B:I,2),1);
        B1=-B(1);
        TEST=3;
        B=I;
        G2=GSL*(RAD^2/(RAD+(H1+H2)/2)^2);
      end
   elseif TEST==3,
     if HTP(I,1)>HT(3),
        B=polyfit(HTP(B:I,1),HTP(B:I,2),1);
        B2=-B(1);
        TEST=4;
        P3=HTP(I,3);
        H3=HTP(I,1);
        B=I-1;
        G3=GSL*(RAD^2/(RAD+(H2+H3)/2)^2);
     end
   else
   end
end
T3=ave(HTP(B:A(1),2)) + 273.15;
G4=GSL*(RAD^2/(RAD+(H3+HTP(A(1),1))/2)^2);


for I=1:A(1),
  if HTP(I,3) >= P1,
    H(I)=(T0/B0)*(1-(HTP(I,3)/P0)^(R*M2F*B0/G1))+H0;
  elseif HTP(I,3) >= P2,
    H1=(T0/B0)*(1-(P1/P0)^(R*M2F*B0/G1))+H0;
    H(I)=(T1/B1)*(1-(HTP(I,3)/P1)^(R*M2F*B1/G2))+H1;
  elseif HTP(I,3)>= P3,
    H2=(T1/B1)*(1-(P2/P1)^(R*M2F*B1/G2))+H1;
    H(I)=(T2/B2)*(1-(HTP(I,3)/P2)^(R*M2F*B2/G3))+H2;
  else
    H3=(T2/B2)*(1-(P3/P2)^(R*M2F*B2/G3))+H2;
    H(I)= -((T3*R*M2F/G4)*log(HTP(I,3)/P3)) + H3;
  end
end
ERROR=HTP(:,1)-H';

axis([0,HTP(A(1),1),min(ERROR)-50,max(ERROR)+50]);
plot(HTP(:,1),ERROR,HTP(:,1),0.03*HTP(:,1),'.')
xlabel('Altitude')
ylabel('Altitude Error ft')
gtext('Altitude Error using model corrected for')
```

```
gtext('variable gravity and actual lapse rates.')
gtext(NAME)
gtext(DATE)
gtext('3%')

meta graph1
```

C. PROGRAM TO PLOT ALTITUDE ERROR USING ACTUAL LAPSE RATES.

This program computes plots the temperature profile so the transition points can be extracted. The program determines the actual transitions above the first two points chosen, and then uses the third point as the actual break for the isothermal region. The temperature and pressure are read off for the start of each region, and a lapse rate is computed for the first three regions. The actual lapse rates are used to compute altitude, along with the temperature and pressure measured at each transition point. The altitude is computed for each transition point and added to the computed altitude for each section to determine total altitude.

```
% This takes an input file of the sounding data, and plots it.

M2F=3.28083989501;
Rad=6348407*M2F;
Rad1=6348407*M2F*9.80665/9.795707;
A=size(HTP);
H=[];
R=287.04;
Gave=9.7257954;

Tu=HTP(1,2)+273.15 - 0.0065*(11000-HTP(1,1)/M2F);
Pu=HTP(1,3)*(1-((.0065*(11000-HTP(1,1)/M2F))/(HTP(1,2)+273.1
5)))^(Gave/1.86576);
```

```
for I=1:A(1),
  if HTP(I,3)>Pu,

H(I,1)=((HTP(1,2)+273.15)/.0019812)*(1-(HTP(I,3)/HTP(1,3)).^
(1.86576/Gave))+HTP(1,1);
  else,
    H(I,1)=-(M2F*287.04*Tu/Gave)*(log(HTP(I,3)/Pu))      +
11000*M2F;
  end;
end;
HG=Rad*H./(Rad1-H);
ERROR1=HTP(:,1)-HG;


axis([0,5000,0,30]);
plot(HTP(:,1),HTP(:,2))
gtext('')
axis;
plot(HTP(:,1),HTP(:,2))
title('Temperature Profile')
xlabel('Altitude')
ylabel('Temperature C')
gtext(NAME)
gtext(DATE)
meta graph1
HT=input('enter the altitude breaks: ');
% plot(HTP(:,1),ERROR)
% xlabel('Altitude')
% ylabel('Altitude Error ft')
% title('Altitude Error caused by SAIP Altitude Model')
% gtext(NAME)
% gtext(DATE)
% meta graph1

T0=HTP(1,2)+273.15;
P0=HTP(1,3);
P=1;
for I=1:A(1),
  if P==1,
     if HTP(I,1)>HT(1) & HTP(I,2)<HTP(I+1,2),
        T1=HTP(I,2)+273.15;
        P1=HTP(I,3);
        B=polyfit(HTP(1:I,1),HTP(1:I,2),1);
        B0=-B(1);
        P=2;B=I;
     end
  elseif P==2,
     if HTP(I,1)>HT(2) & HTP(I,2)>HTP(I+1,2),
        T2=HTP(I,2)+273.15;
        P2=HTP(I,3);
        B=polyfit(HTP(B:I,1),HTP(B:I,2),1);
```

```
        B1=-B(1);
        P=3;B=I;
      end
   elseif P==3,
      if HTP(I,1)>=HT(3),
         T3=ave(HTP(I:A(1),2)) + 273.15;
         P3=HTP(I,3);
         B=polyfit(HTP(B:I,1),HTP(B:I,2),1);
         B2=-B(1);
         P=4;
     end
   else
   end
end

for I=1:A(1),
  if HTP(I,3) >= P1,

H(I)=(T0/B0)*(1-(HTP(I,3)/P0)^(R*3.28084*B0/Gave))+HTP(1,1);
  elseif HTP(I,3) >= P2,
    H1=(T0/B0)*(1-(P1/P0)^(R*3.28084*B0/Gave))+HTP(1,1);
    H(I)=(T1/B1)*(1-(HTP(I,3)/P1)^(R*3.28084*B1/Gave))+H1;
  elseif HTP(I,3) >= P3,
   H2=(T1/B1)*(1-(P2/P1)^(R*3.28084*B1/Gave))+H1;
   H(I)=(T2/B2)*(1-(HTP(I,3)/P2)^(R*3.28084*B2/Gave))+H2;
  else,
    H3=(T2/B2)*(1-(P3/P2)^(R*3.28084*B2/Gave))+H2;
    H(I)=-M2F*R*T3/Gave*log(HTP(I,3)/P3) + H3;
  end
end

HG=Rad*H./(Rad1-H);
ERROR=HTP(:,1)-HG;

axis([0,HTP(A(1),1),min(min(ERROR),
      min(ERROR1))-50,max(max(ERROR), max(ERROR1))+50]);
plot(HTP(:,1),ERROR,HTP(:,1),0.03*HTP(:,1),'.',
     HTP(:,1),-0.03*HTP(:,1),'.',HTP(:,1),ERROR1)
xlabel('Altitude')
ylabel('Altitude Error ft')
gtext('Current Model')
gtext('Corrected for actual lapse rates')
gtext(NAME)
gtext(DATE)
gtext('3%')
gtext('3%')
grid
meta graph1
axis;
```

APPENDIX B. GRAPHS OF AERODYNAMIC DATA

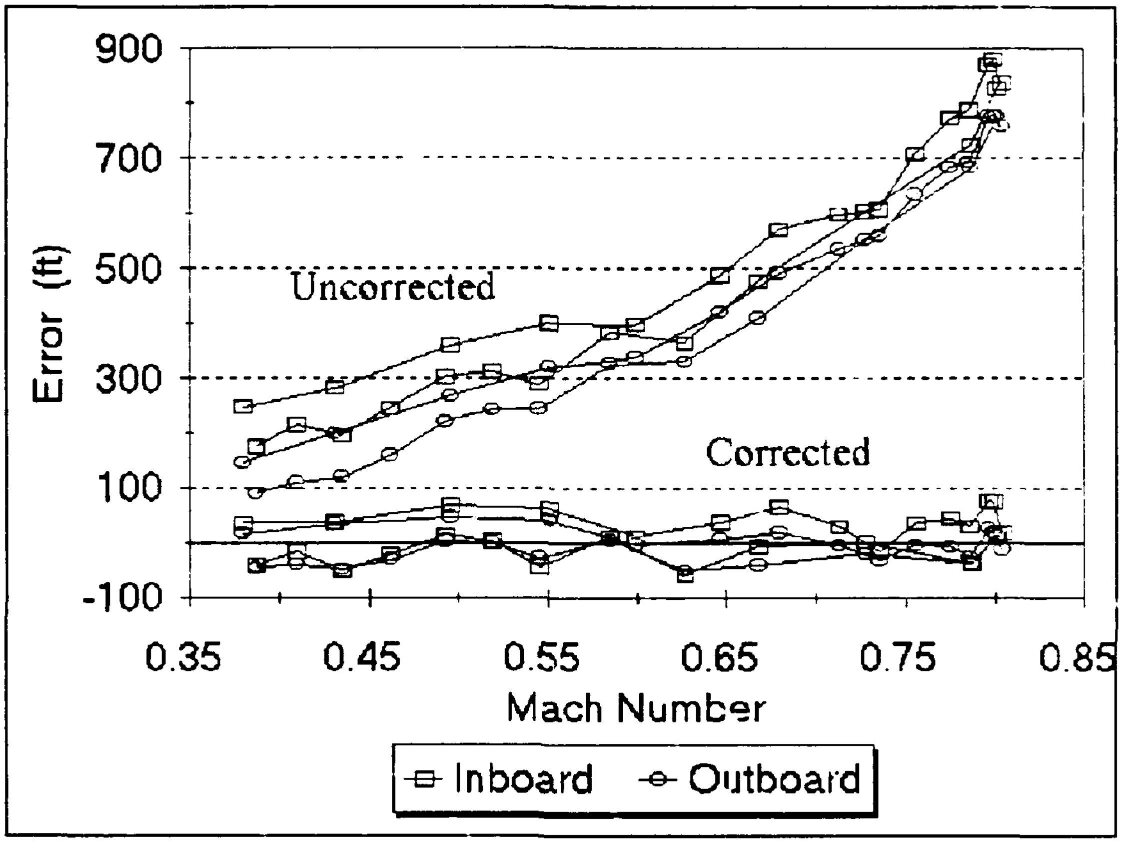

Figure 15 Corrected and Uncorrected Altitude Errors for the SAIP for Run 2, 4,000 ft

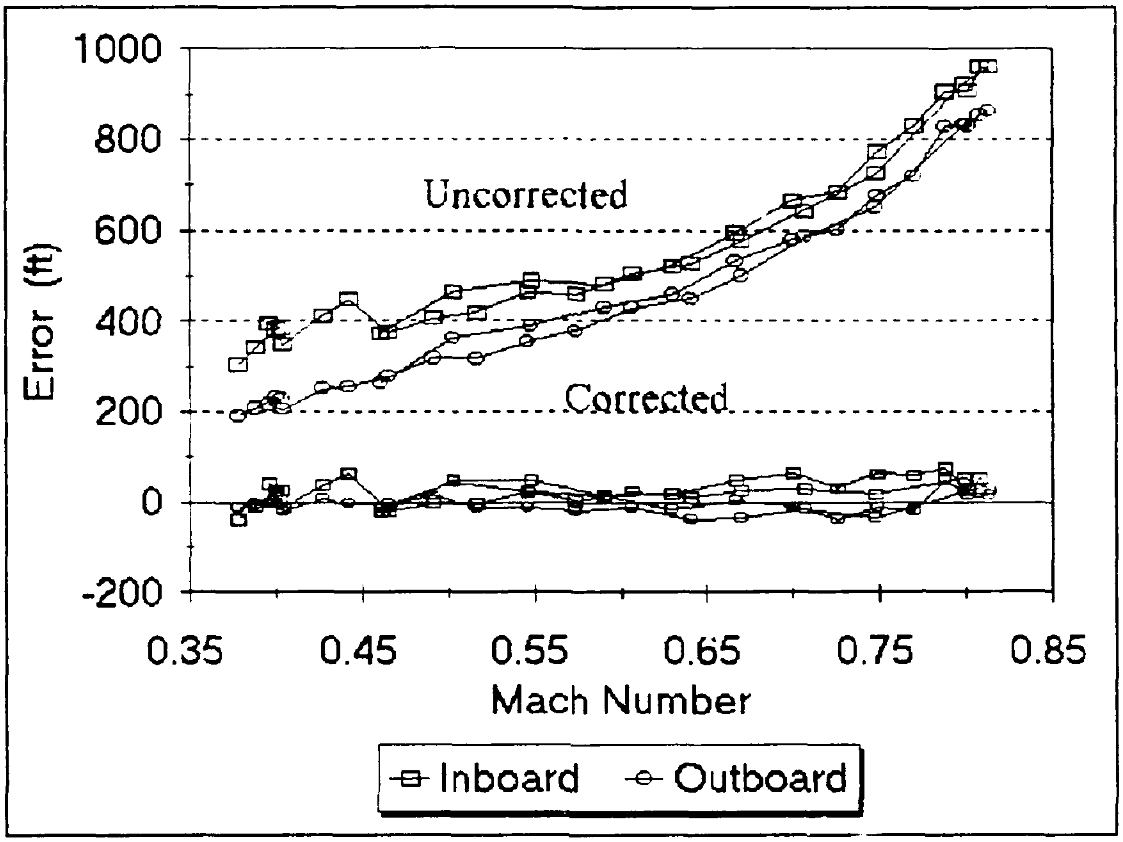

Figure 16 Corrected and Uncorrected Altitude Errors for the SAIP for Run 3, 10,000 ft

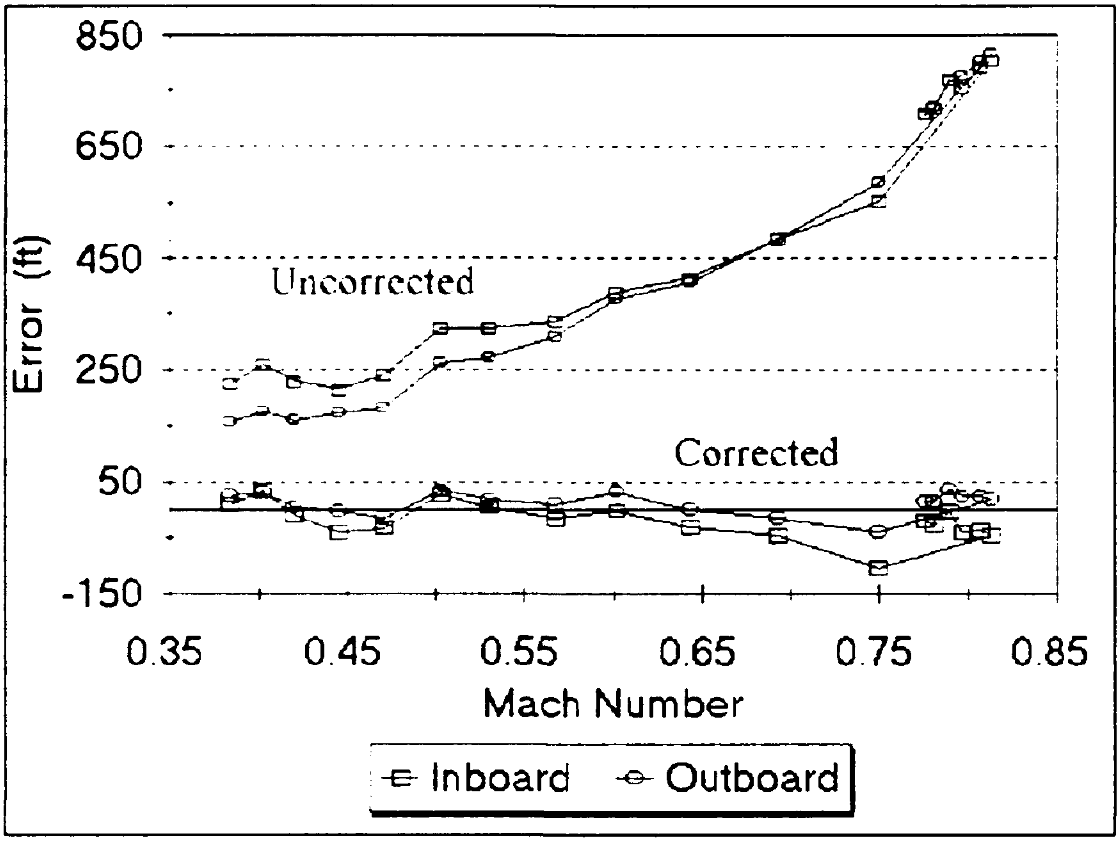

Figure 17 Corrected and Uncorrected Altitude Errors For the SAIP for Run 4, 4,000 ft

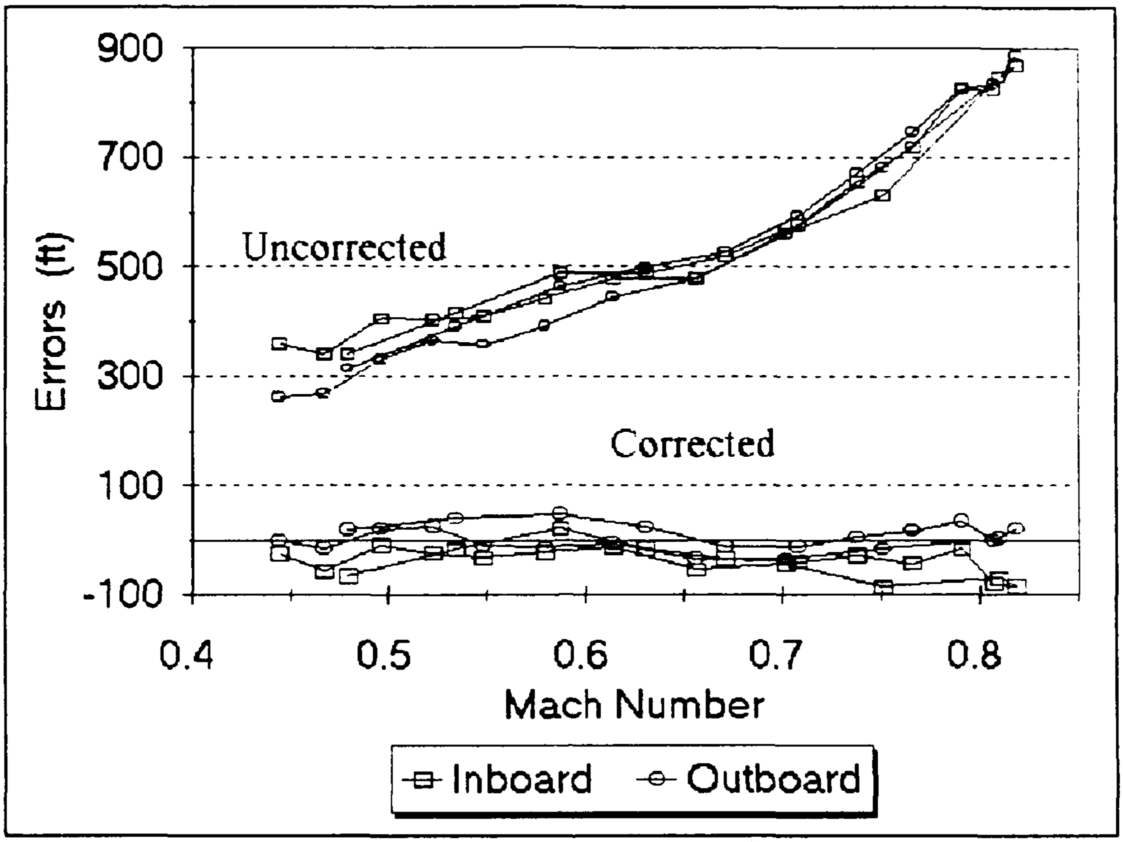

Figure 18 Corrected and Uncorrected Altitude Errors for the SAIP for Run 5, 10,000 ft

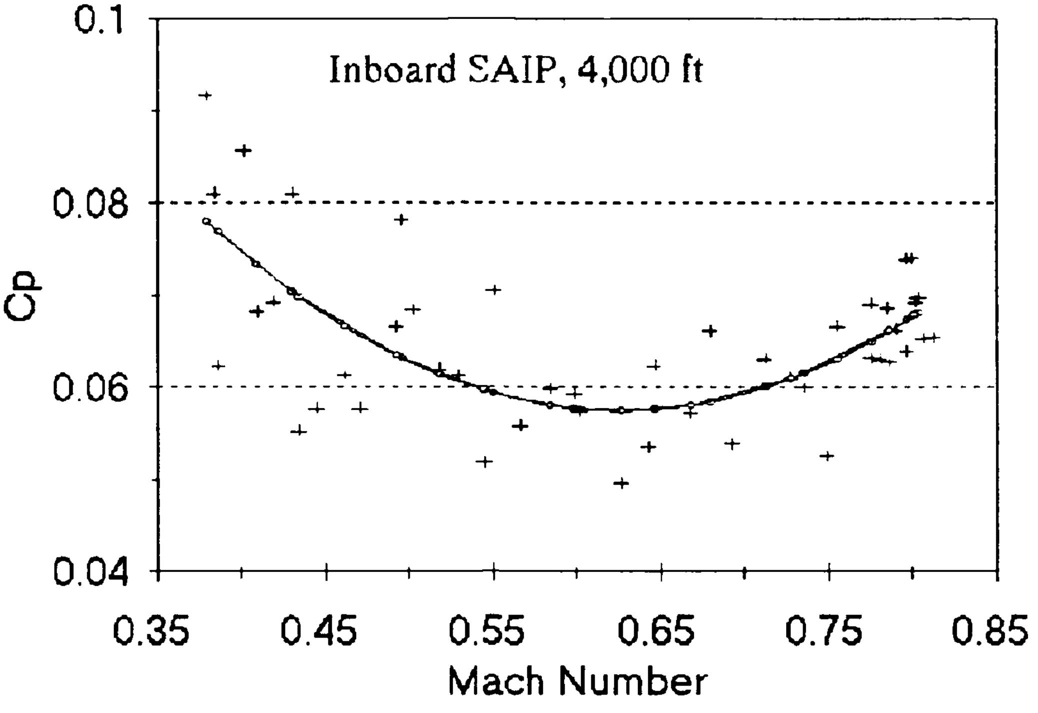

Figure 19 Quadratic Curve Fit to the Data for Cp for the Inboard Station at 4,000 ft

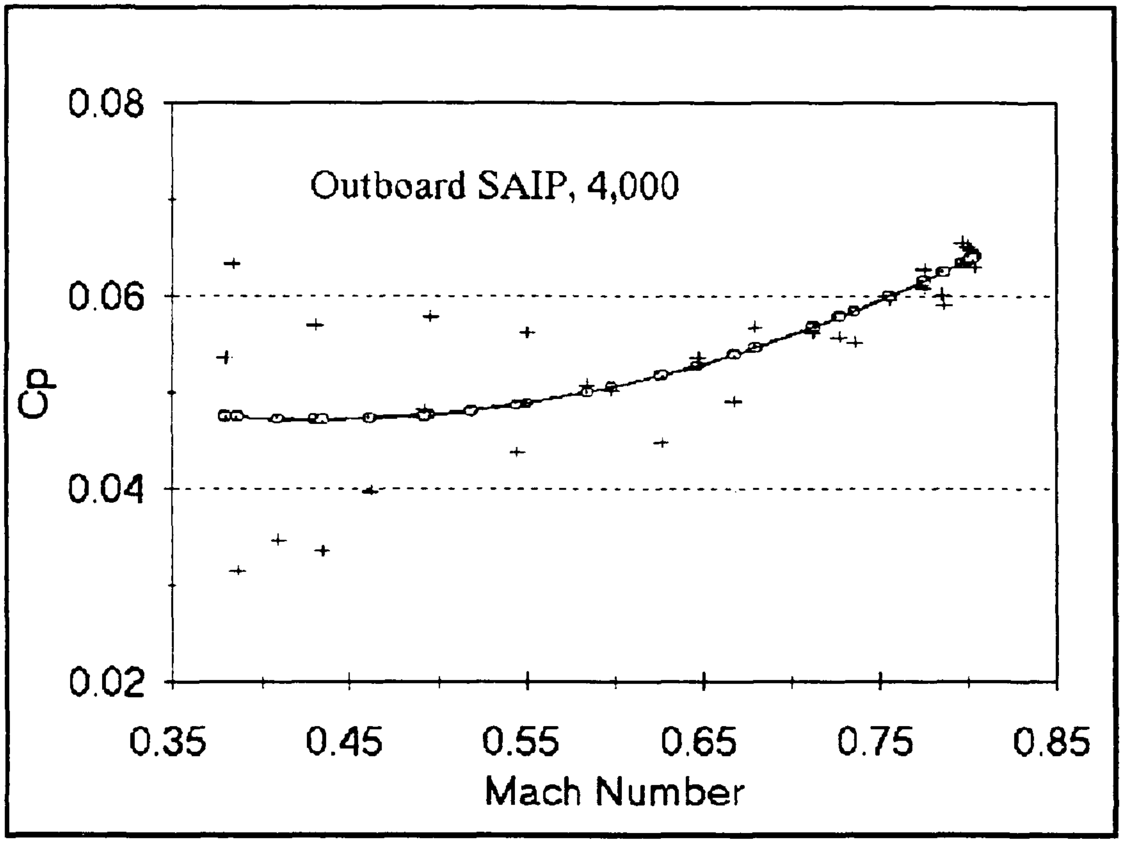

Figure 20 Quadratic Curve Fit for the Data for Cp for the Outboard Station at 4,000 ft

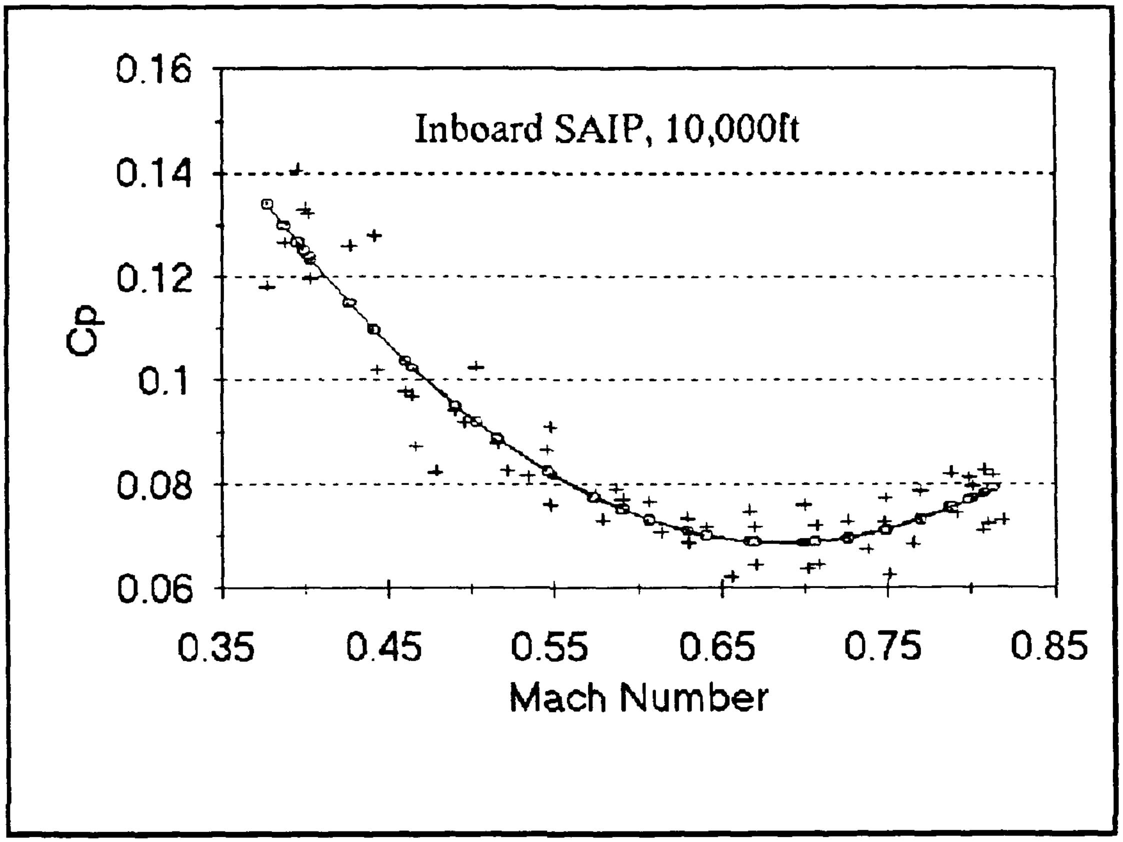

Figure 21 Quadratic Curve Fit for the Data for Cp for the Inboard Station at 10,000 ft

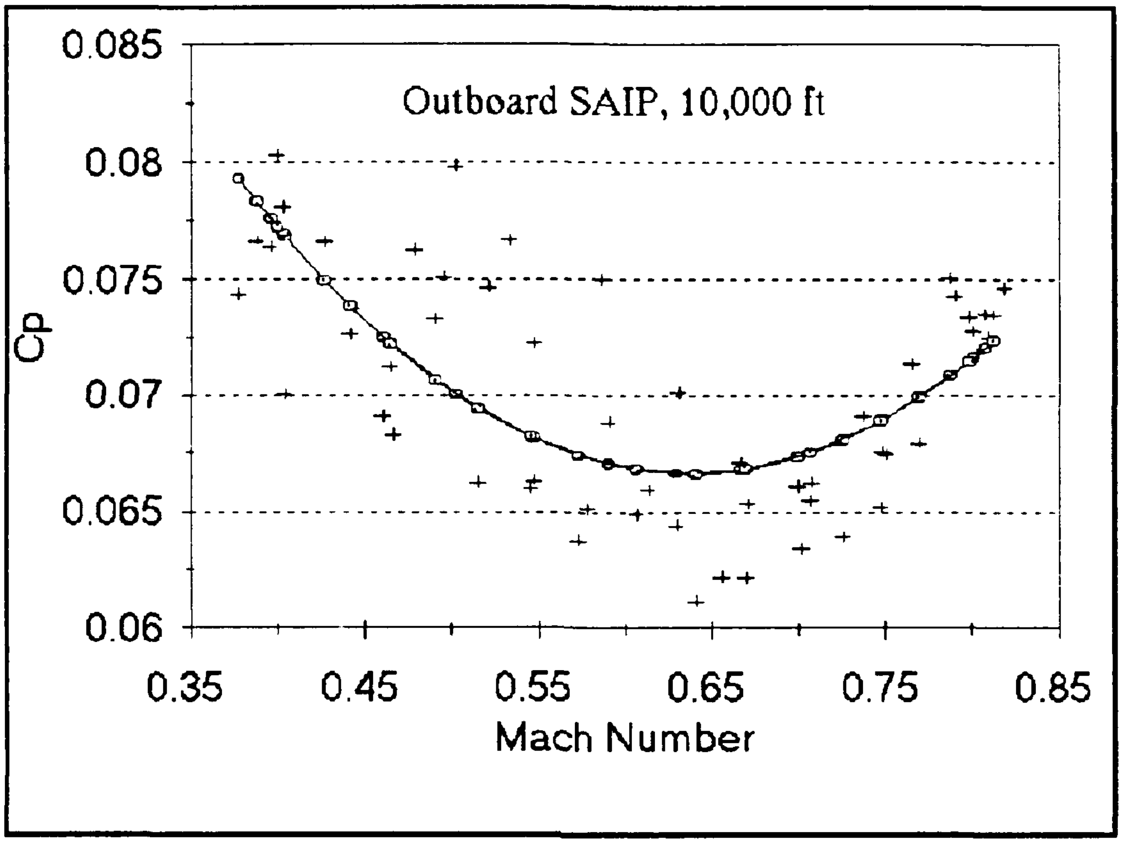

Figure 22 Quadratic Curve Fit for the Data for Cp for the Outboard Station at 10,000 ft

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